Efficient Formally Secure Compilers to a Tagged Architecture

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Inria Paris

Prosecco team

5 year vision

ERC SECOMP: https://secure-compilation.github.io

Computers are insecure

- **devastating low-level vulnerabilities**
- **teasing out 2 important security problems:**

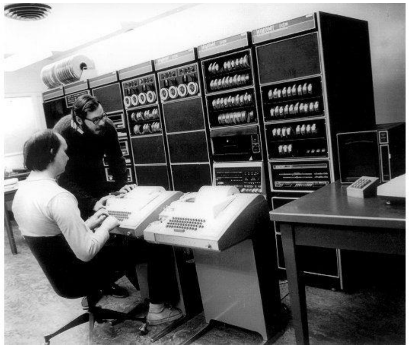
1. inherently insecure low-level languages

- **memory unsafe**: any buffer overflow can be catastrophic allowing remote attackers to gain complete control

2. unsafe interoperability with lower-level code

- even code written in **safer languages** has to interoperate with **insecure low-level libraries**
- **unsafe interoperability:** high-level safety guarantees lost

How did we get here?



- **programming languages, compilers, and hardware architectures**
  – designed in an era of **scarce hardware resources**
  – too often **trade off security for efficiency**
- **the world has changed** (2017 vs 1972*)
  – security matters, hardware resources abundant
  – time to revisit some tradeoffs

* "...the number of UNIX installations has grown to 10, with more expected..."
-- *Dennis Ritchie and Ken Thompson, June 1972*

Key enabler: Micro-Policies

software-defined, hardware-accelerated, tag-based monitoring

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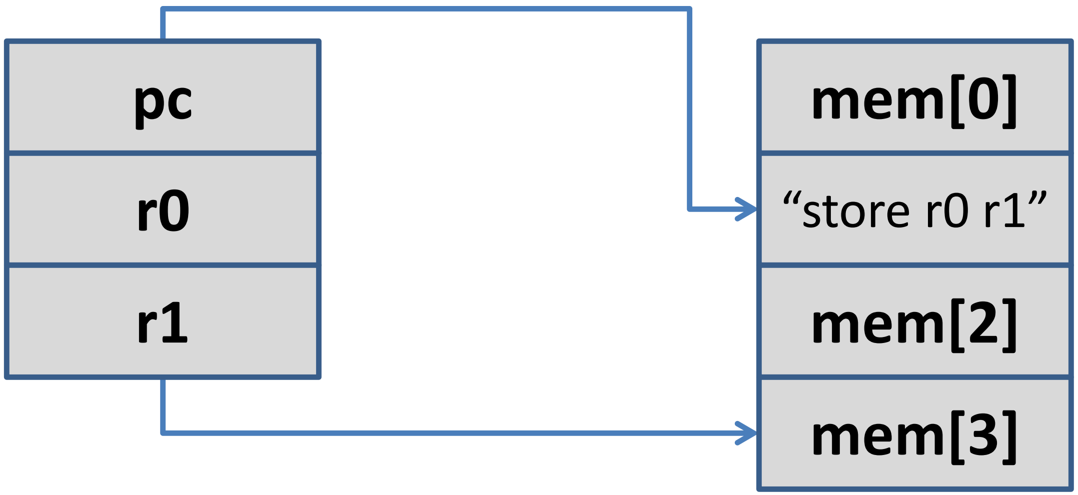

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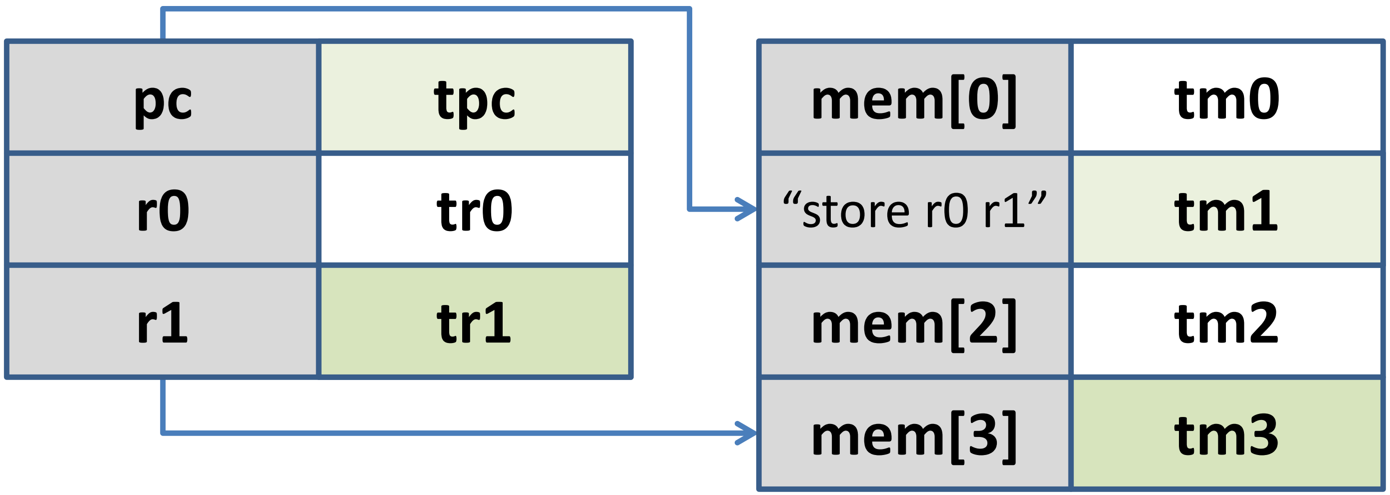

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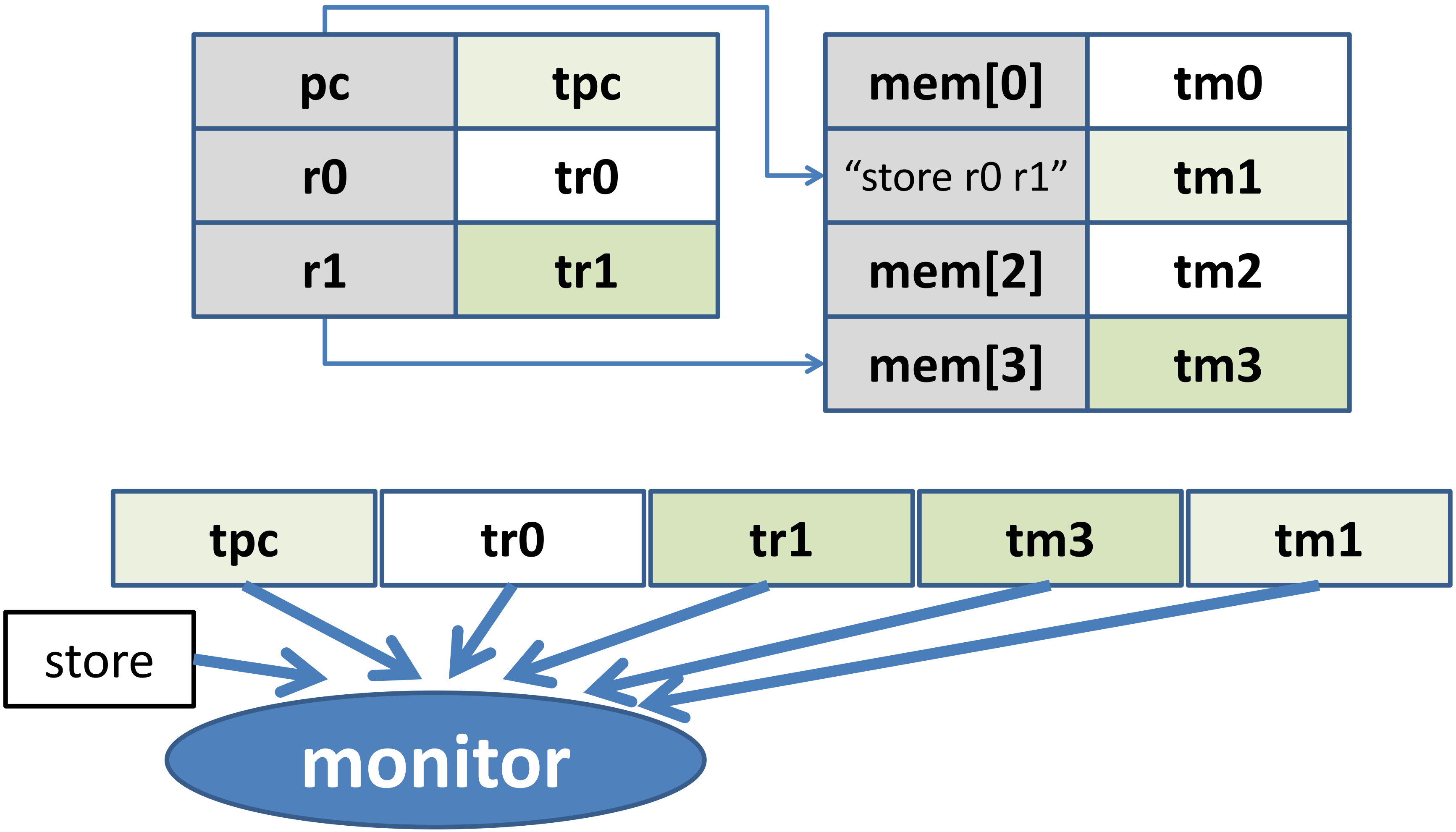

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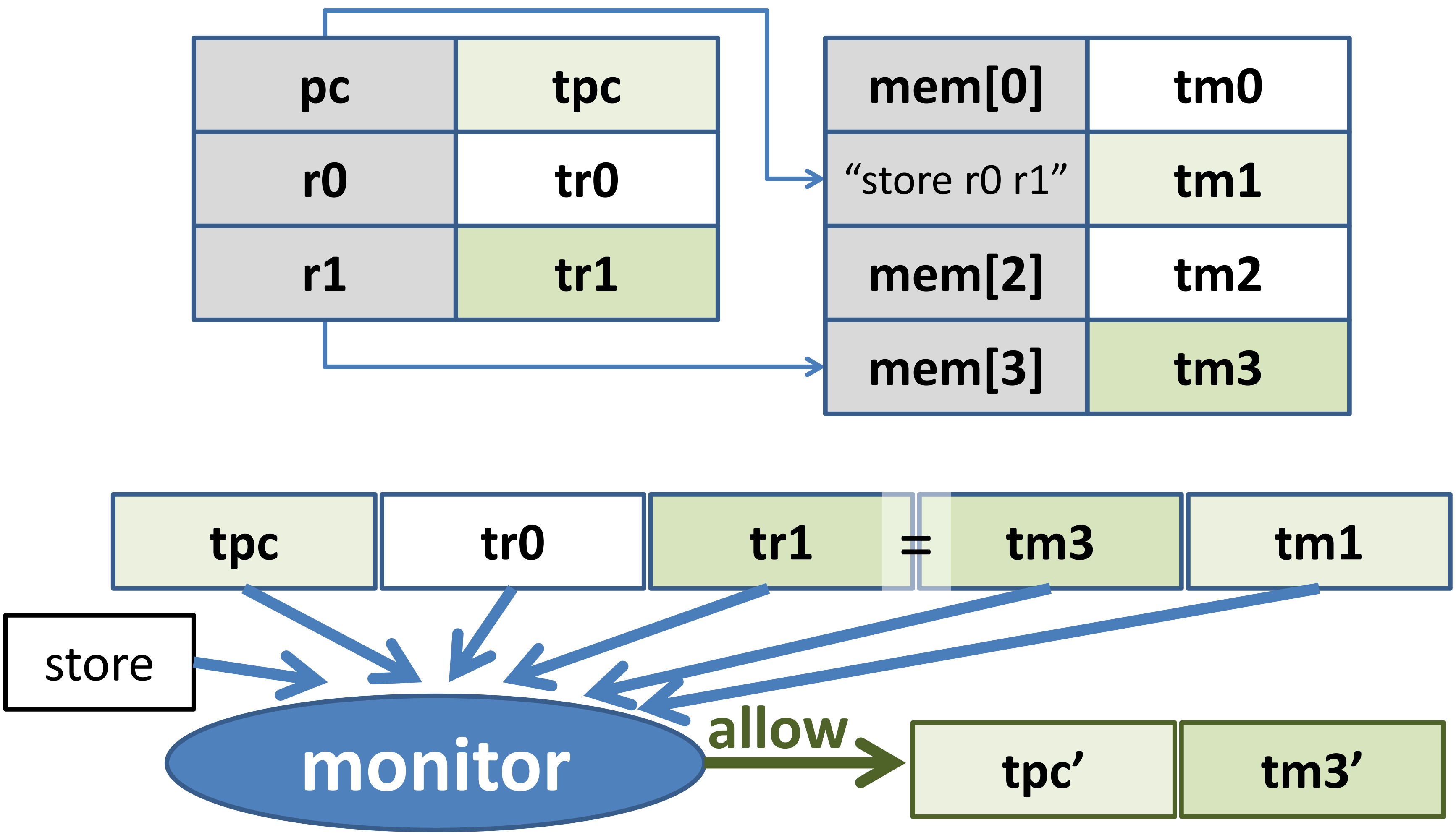

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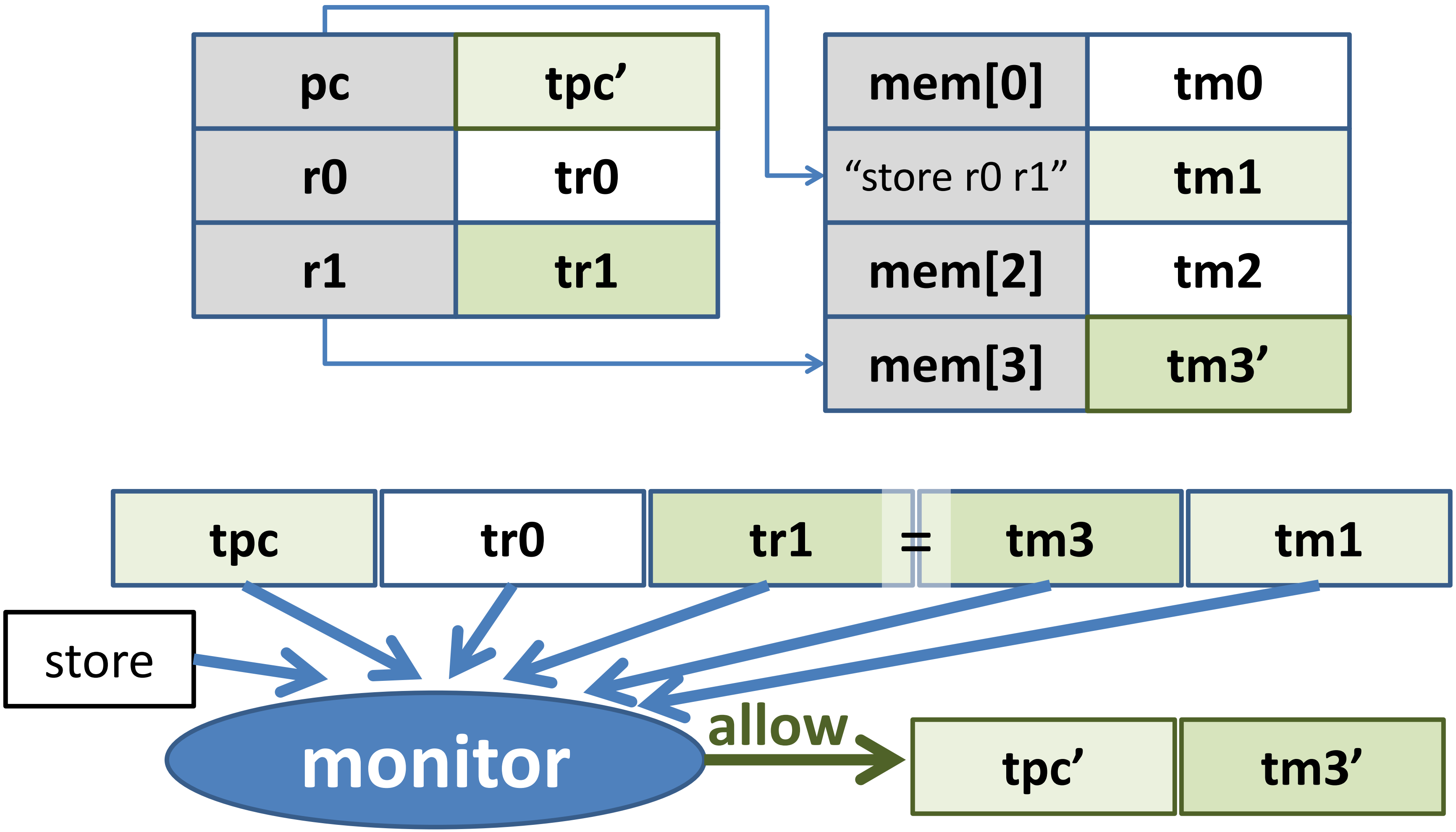

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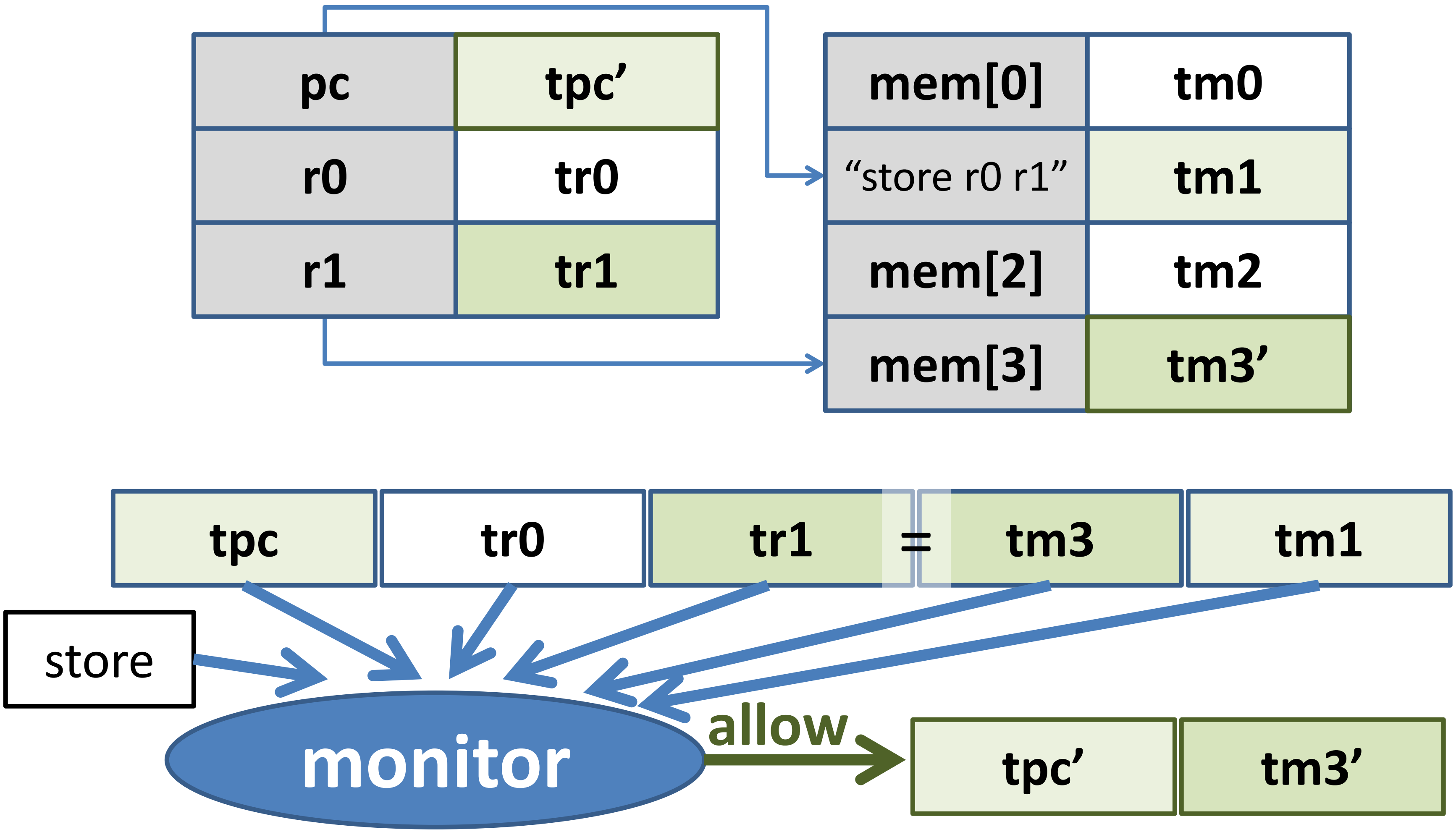

software monitor's decision is hardware cached

Key enabler: Micro-Policies

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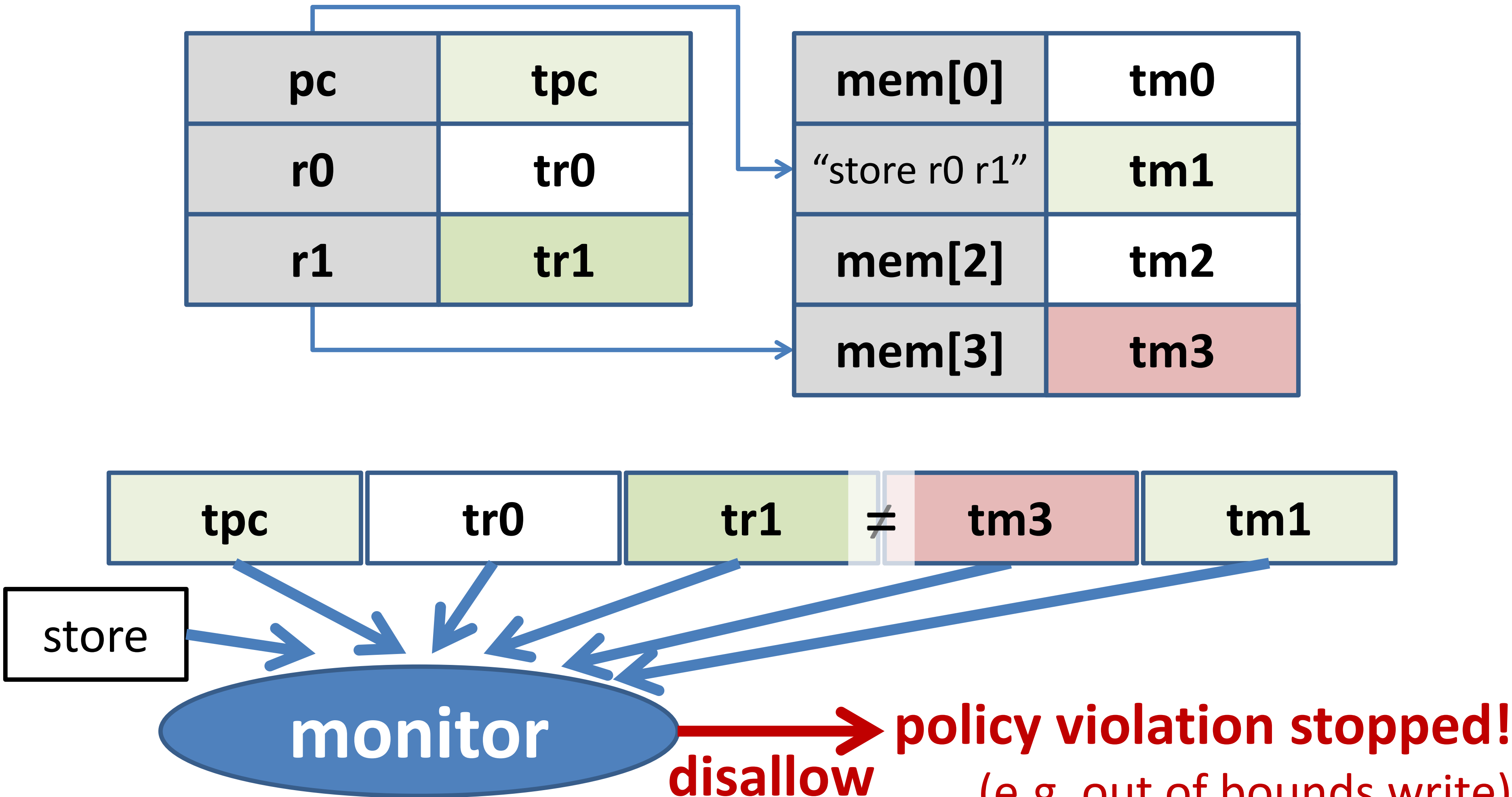


Micro-policies are cool!

- **low level + fine grained**: unbounded per-word metadata, checked & propagated on each instruction
- **flexible**: tags and monitor defined by software
- **efficient**: software decisions hardware cached
- **expressive**: complex policies for secure compilation

- **secure** and **simple** enough to verify security in Coq
- **real**: FPGA implementation on top of RISC-V

Expressiveness

Way beyond MPX, SGX, SSM, etc

- information flow control (IFC) [POPL'14]
- monitor self-protection
- protected compartments
- dynamic sealing
- heap memory safety
- code-data separation
- control-flow integrity (CFI)
- taint tracking
- ...

Verified (in Coq) [Oakland'15]

Evaluated (<10% runtime overhead) [ASPLOS'15]

spec

Micro-Policies team

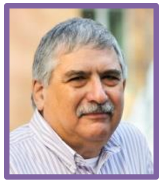
- **Formal methods** & **architecture** & **systems**
- **Current team**:
  - *Inria Paris*: **Cătălin Hrițcu, Guglielmo Fachini, Marco Stronati, Théo Laurent**
  - *UPenn*: **André DeHon**, **Benjamin Pierce**, **Arthur Azevedo de Amorim**, **Nick Roessler**
  - *Portland State*: **Andrew Tolmach**
  - *MIT:* **Howie Shrobe, Stelios Sidiroglou-Douskos**
  - *Industry*: **Draper Labs**
- **Spinoff of past project: DARPA CRASH/SAFE (2011-2014)**









DRAPER

SECOMP grand challenge

Use micro-policies to build **the first efficient formally secure compilers** for **realistic programming languages**

1. **Provide secure semantics for low-level languages**
   – C with protected components and memory safety
2. **Enforce secure interoperability with lower-level code**
   – ASM, C, and Low*

[= safe C subset embedded in F* for verification]

Secure Compilation

holy grail of preserving security all the way down

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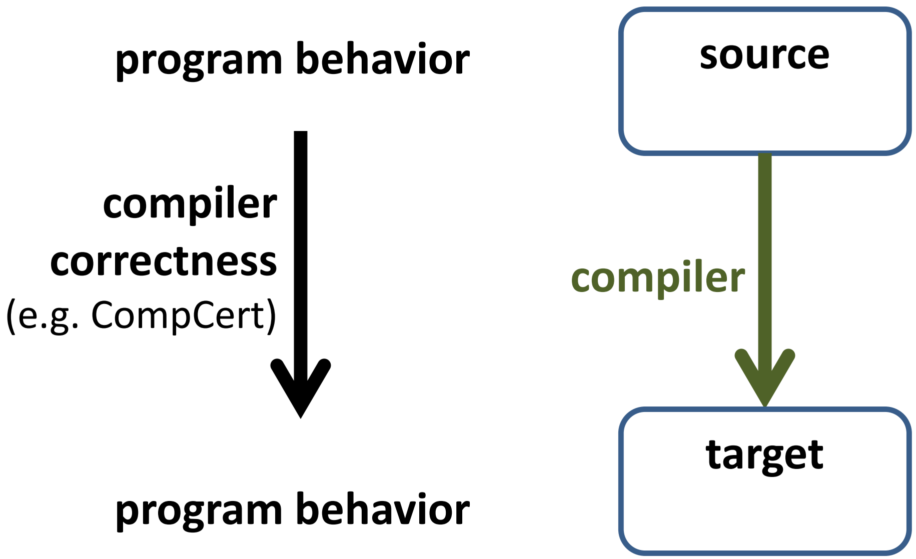

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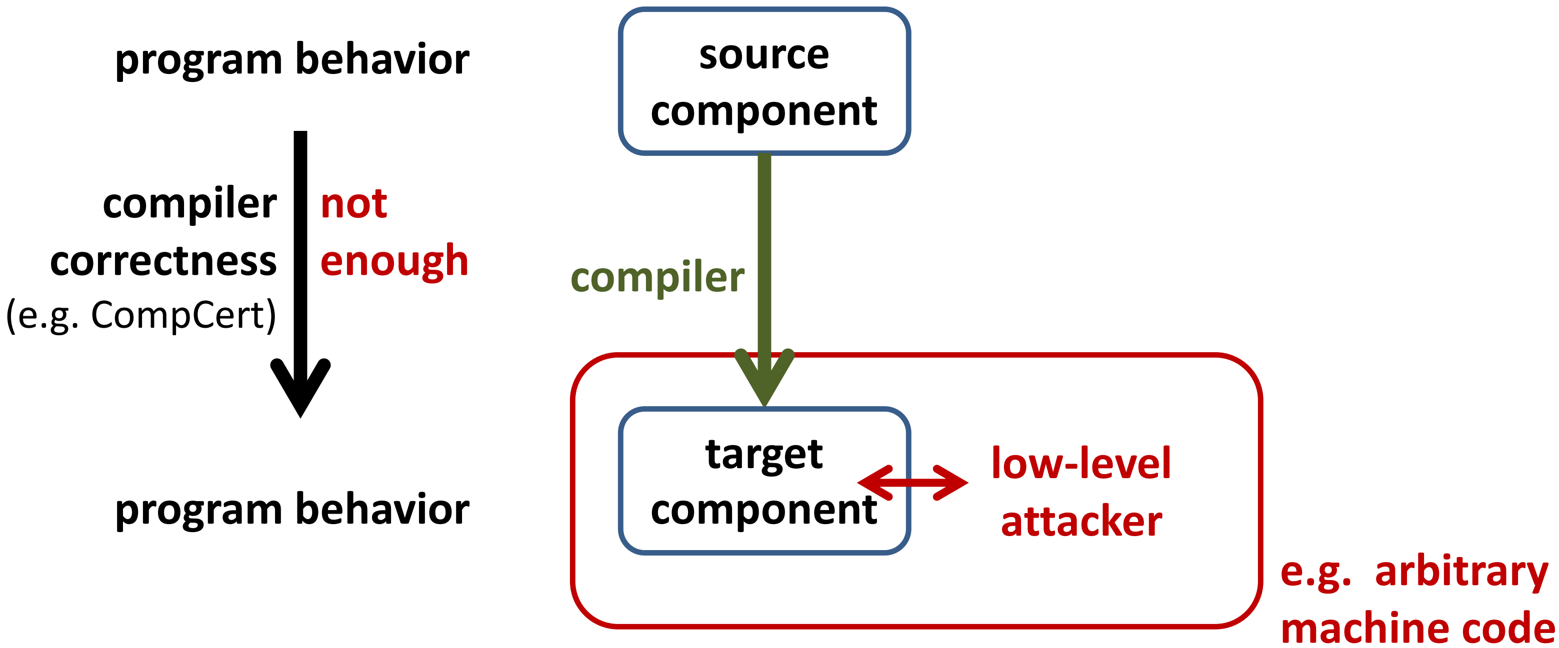

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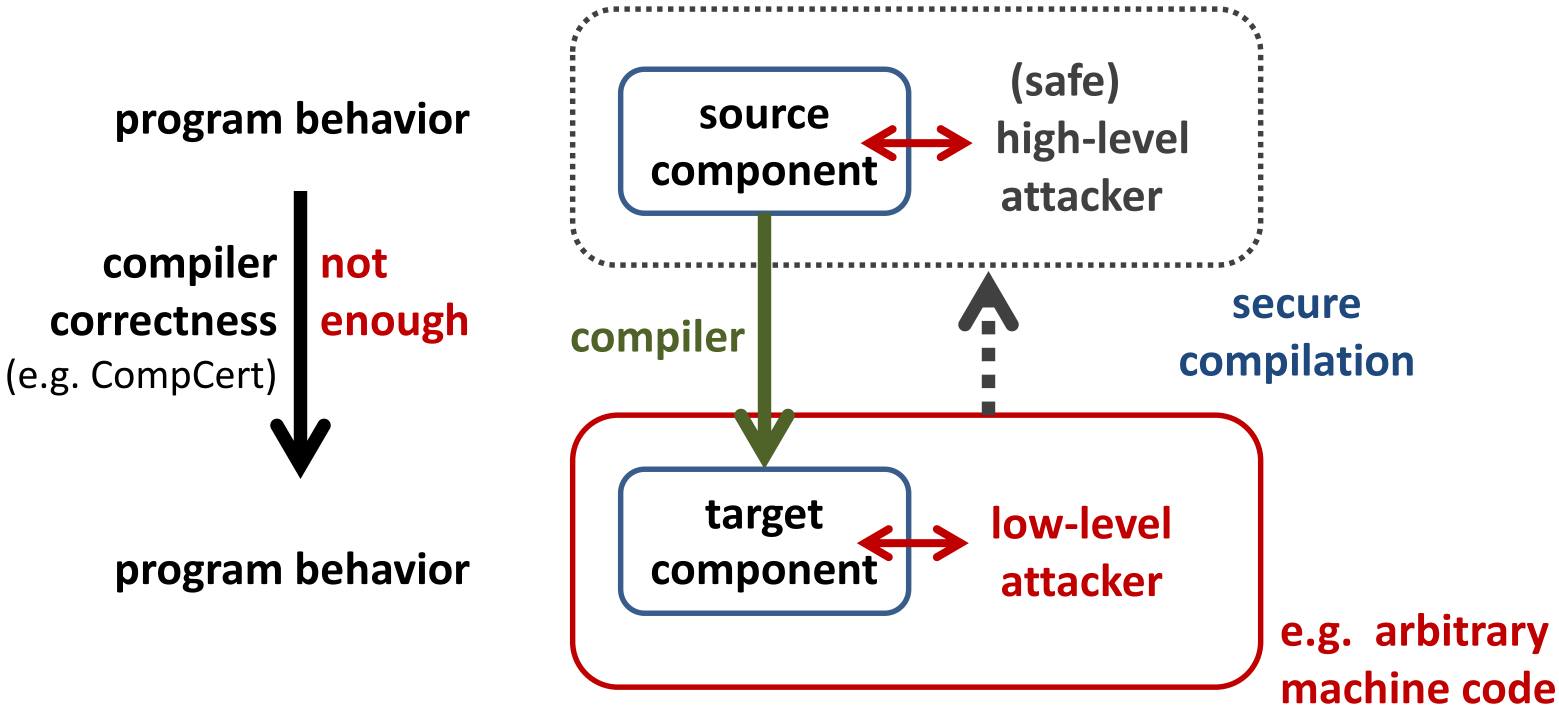

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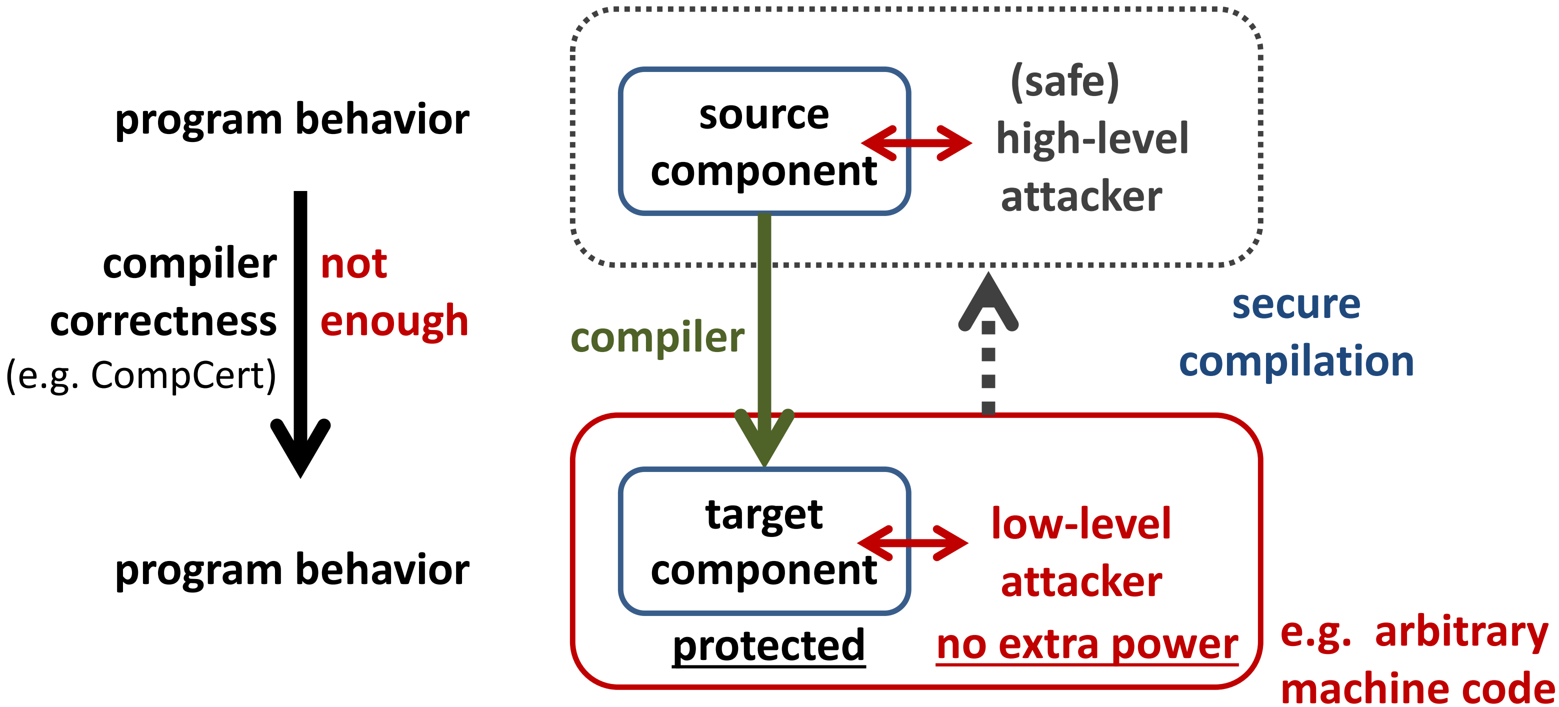


Secure Compilation

holy grail of preserving security all the way down

source component ↔ **(safe) high-level attacker**

program behavior

compiler correctness **not enough**

(e.g. CompCert)

program behavior

secure

secure compilation

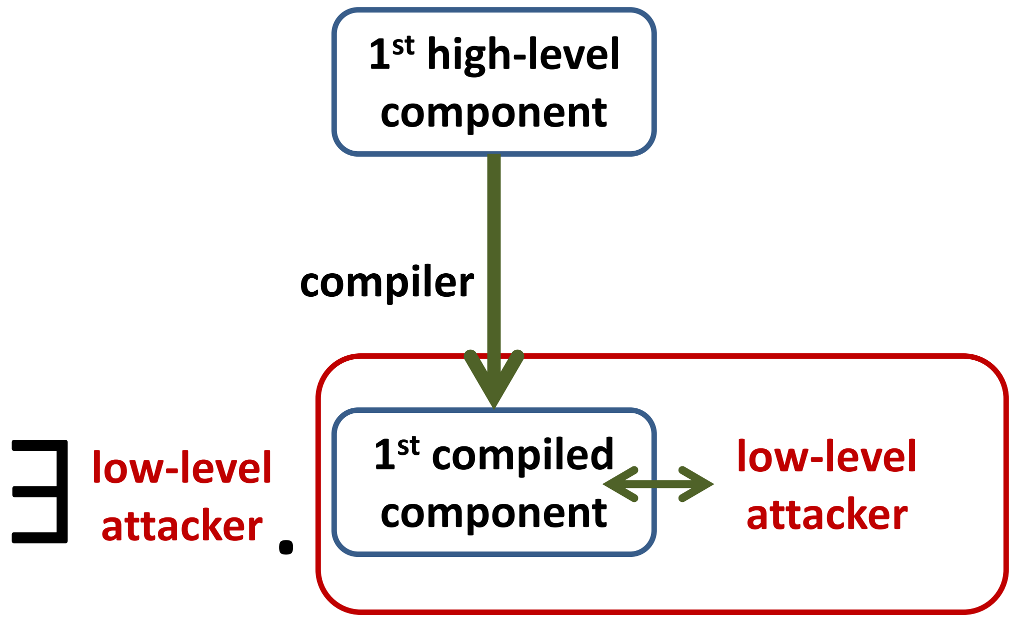
secure

Benefit: sound security reasoning in the source language

forget about compiler chain (linker, loader, runtime system)

forget that libraries are written in a lower-level language

Our original secure compilation target:
fully abstract compilation
(preservation of observational equivalence)



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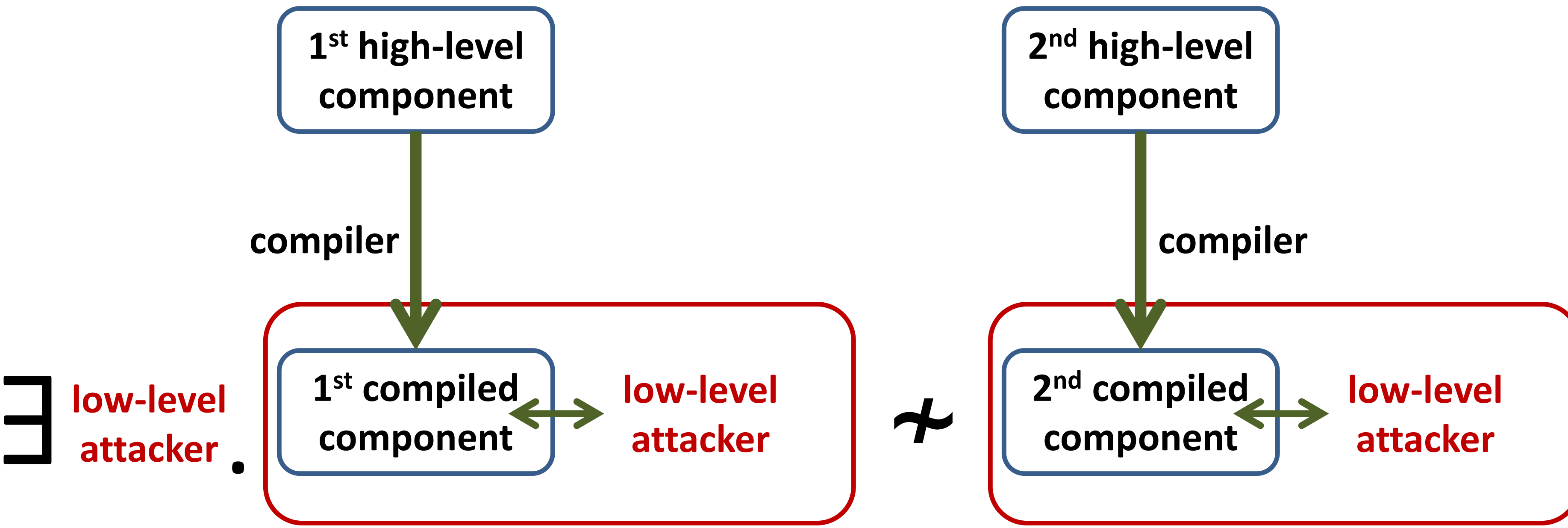

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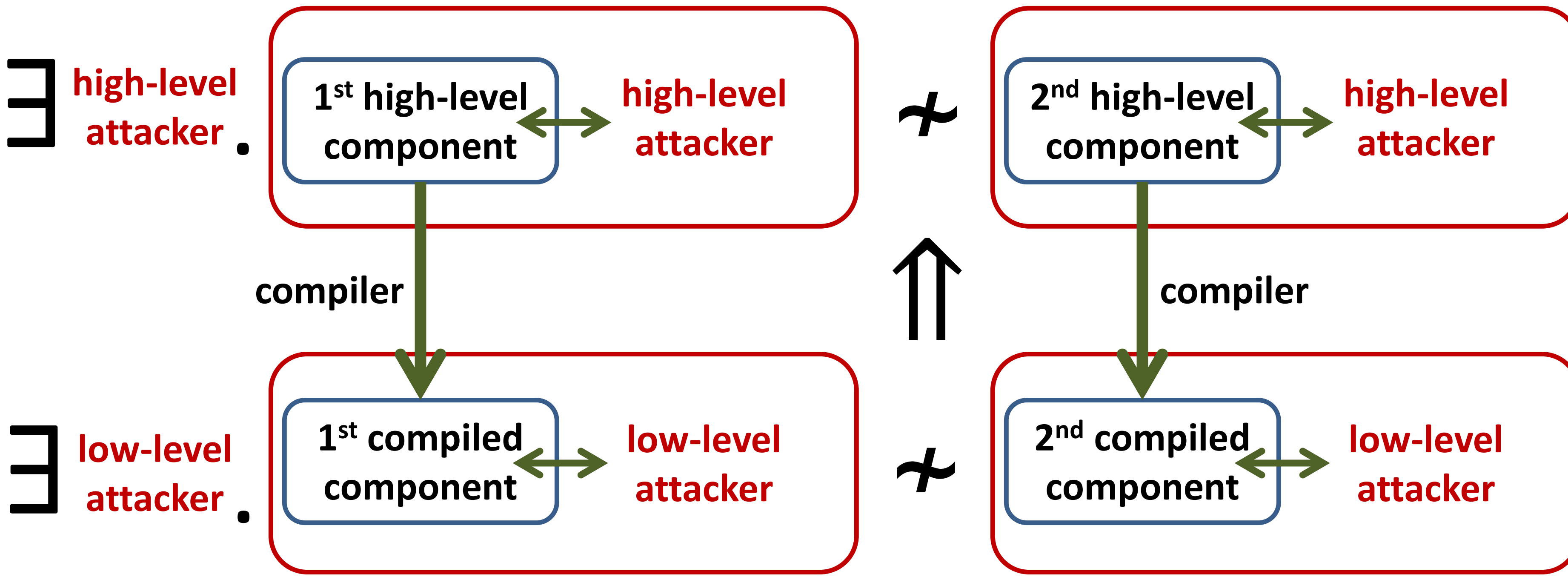

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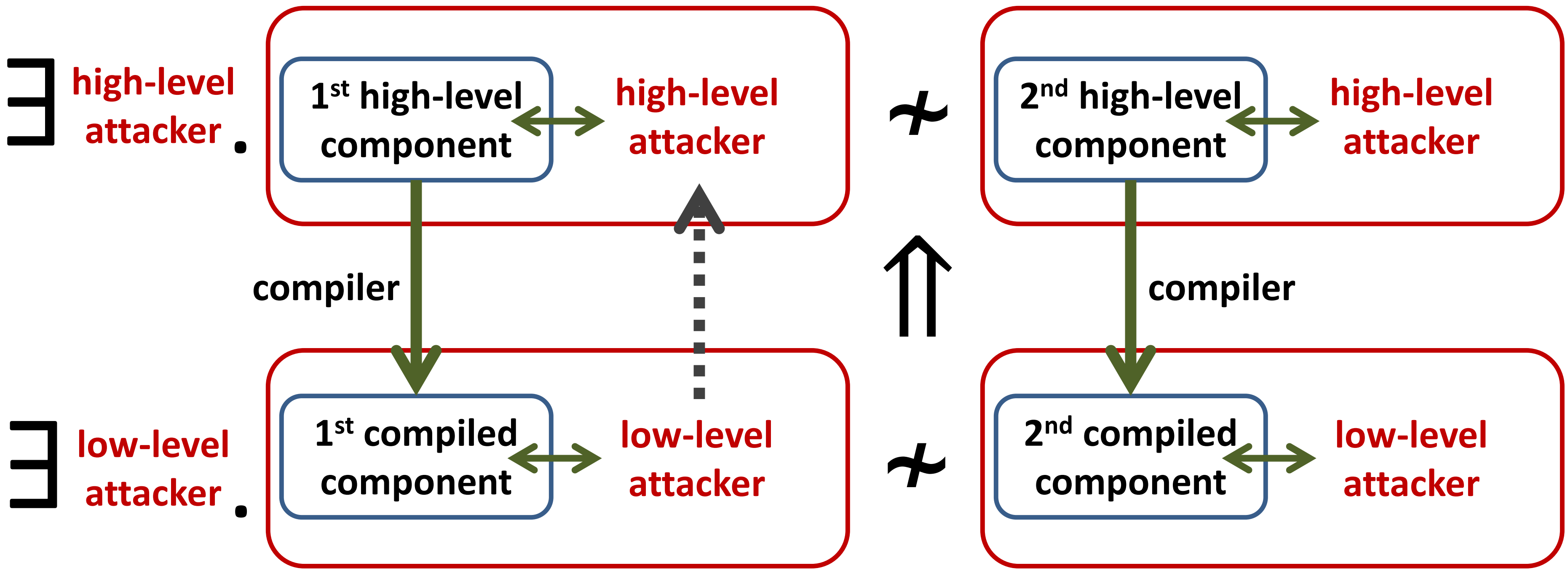

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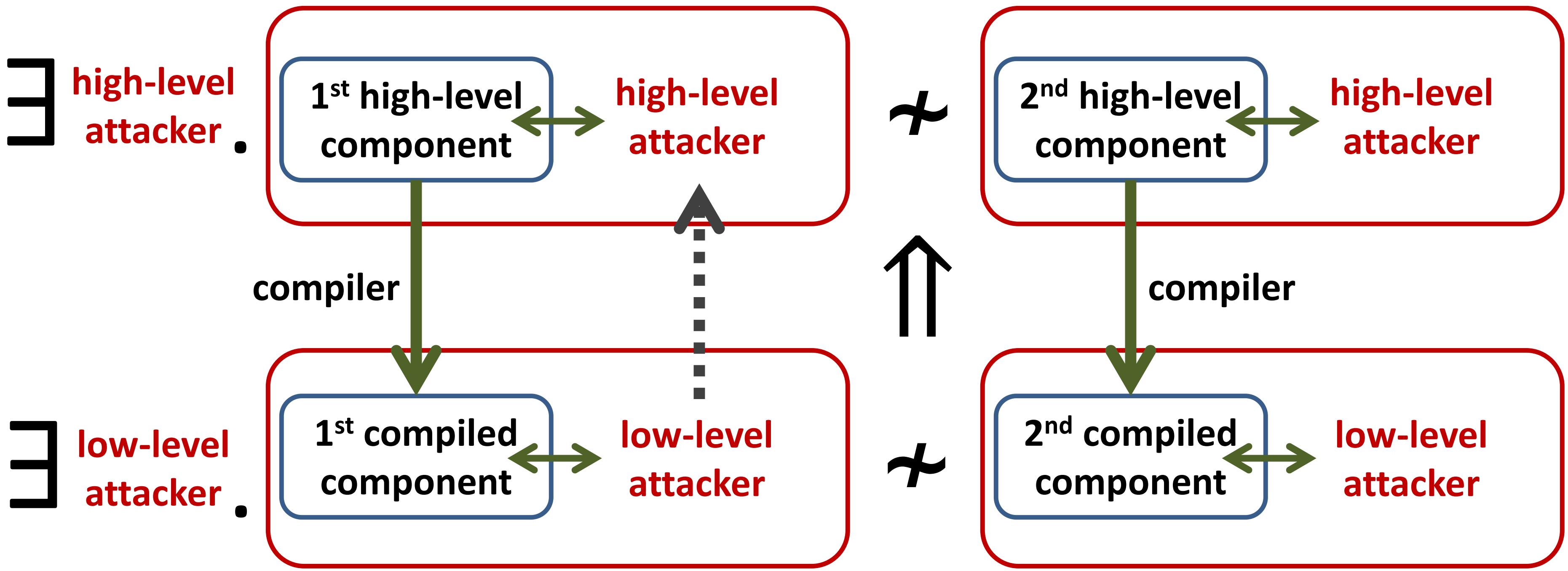
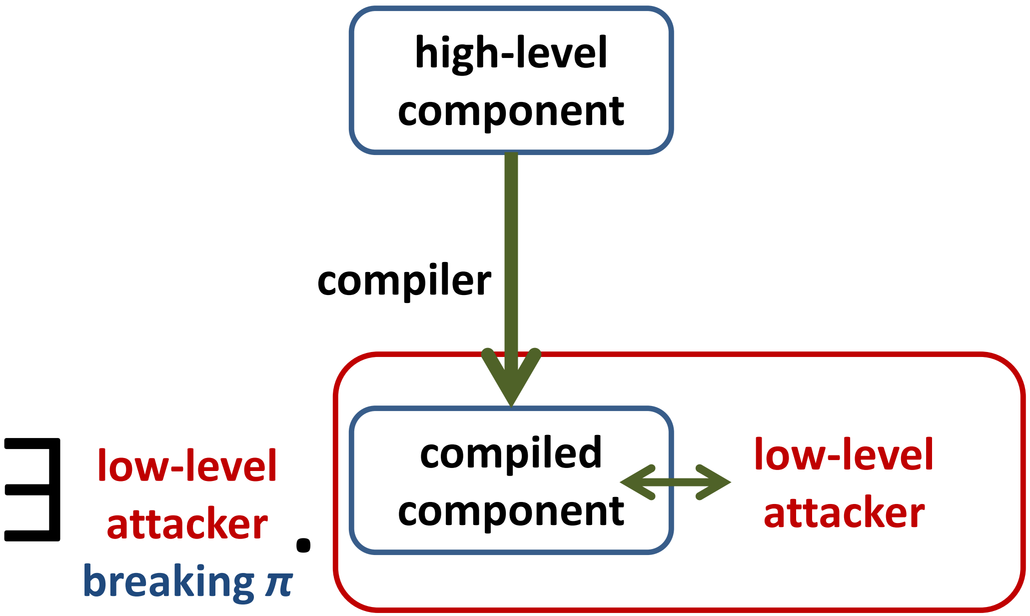


Problems: (1) **very hard to *realistically* achieve**
(hopeless against timing side channels;
more realistic: preservation of noninterference)
(2) **very difficult to prove** ……

Our new first target: robust compilation

∀ trace properties π



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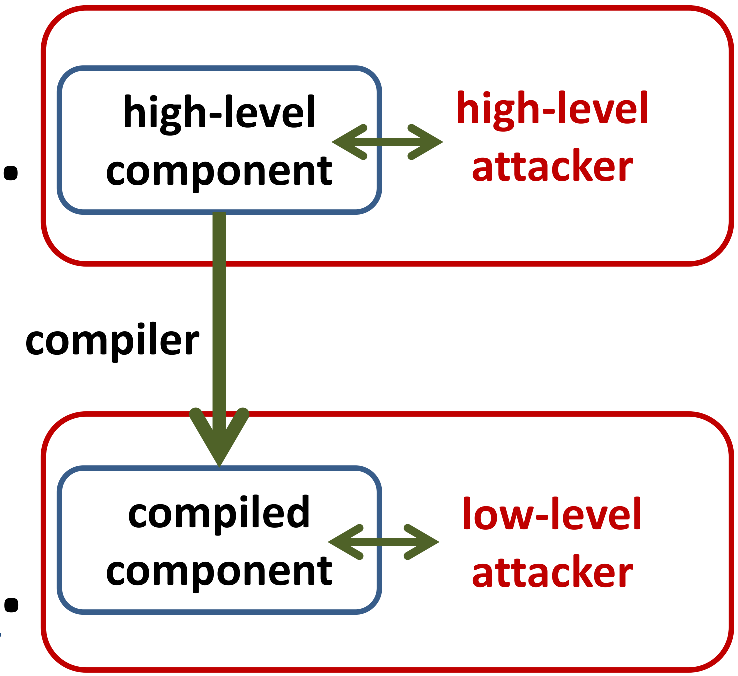

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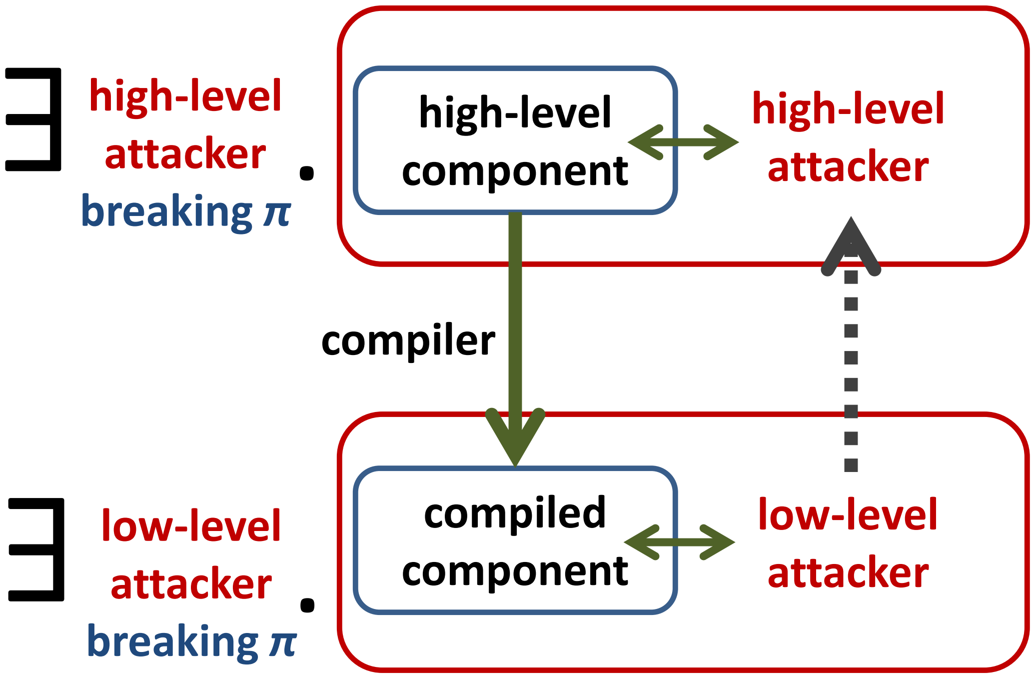

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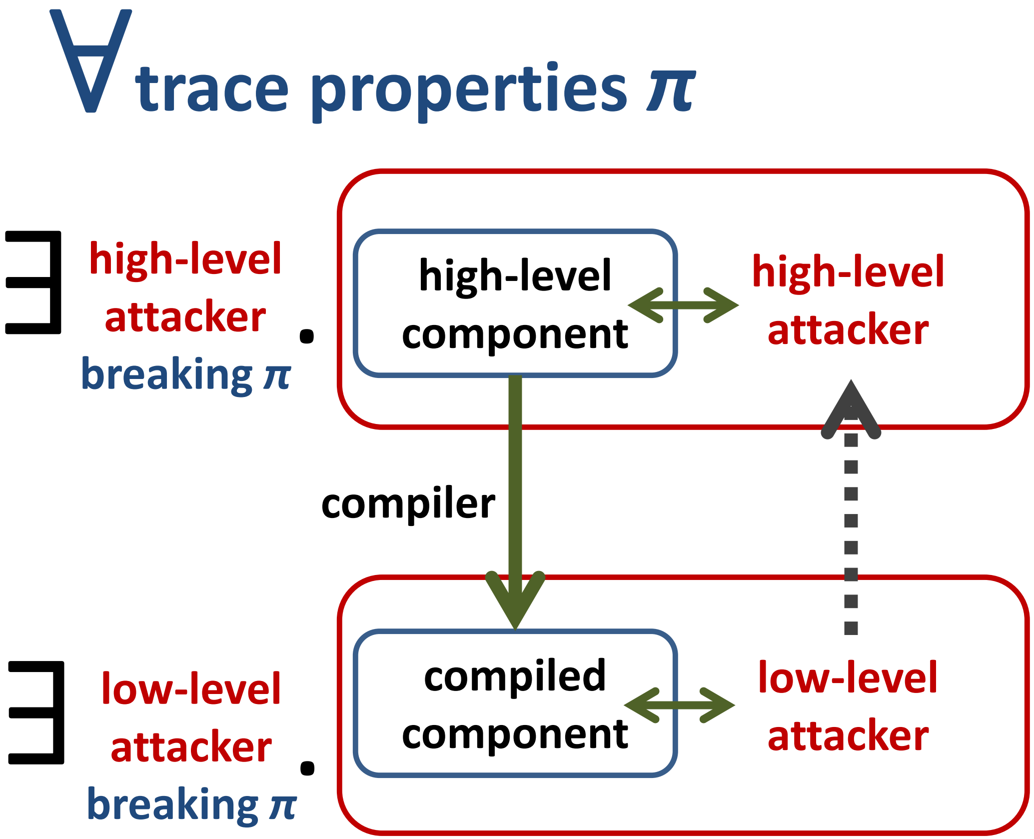

- **robust satisfaction preserved** (adversarial context)

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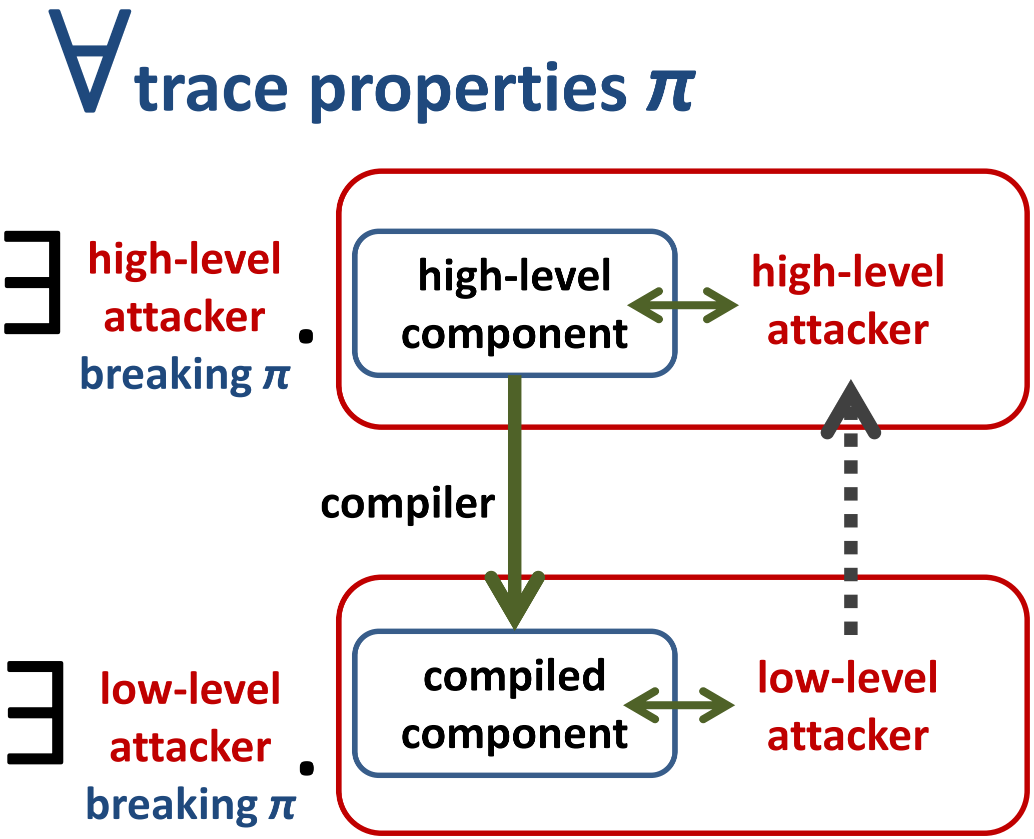

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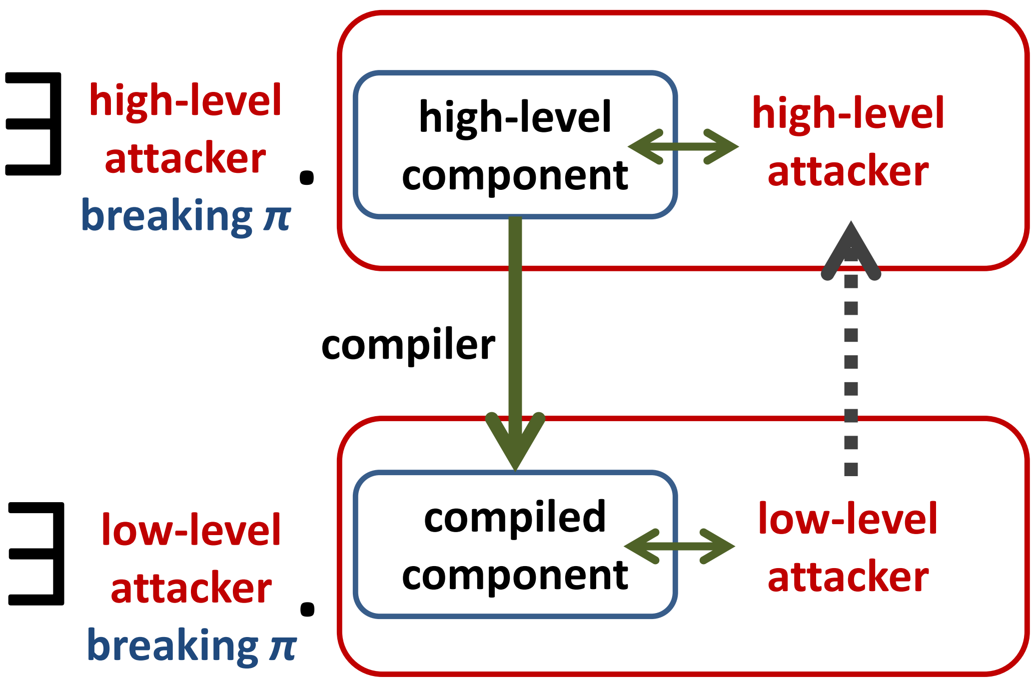

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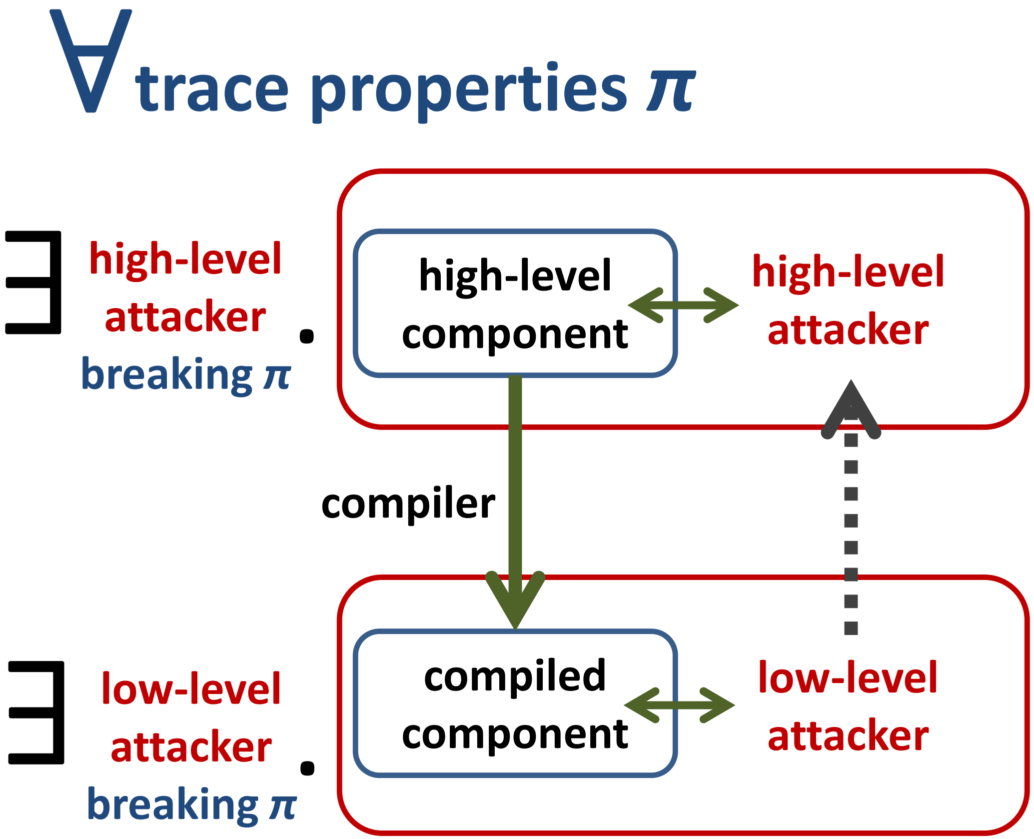

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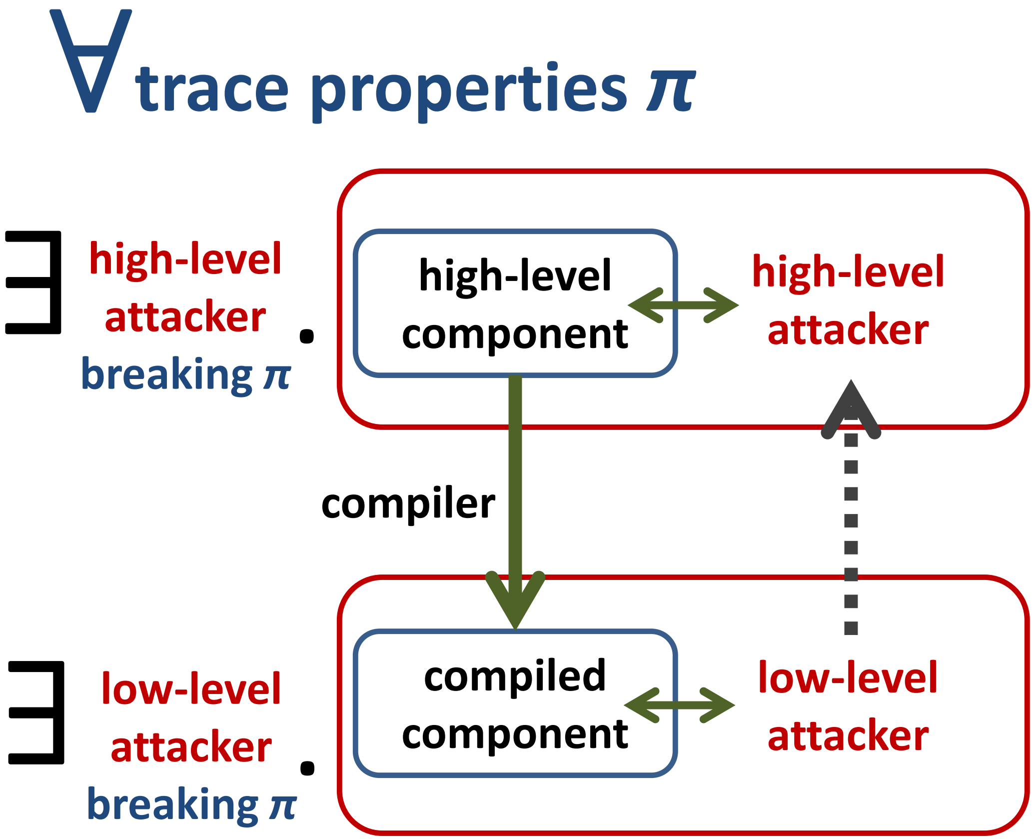

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Advantages: **easier to realistically achieve and prove**

still useful: preservation of **invariants** and other **integrity properties**

SECOMP: achieving secure compilation at scale

Low* language
(safe C subset in F*)

miTLS*

C language
+ components
+ memory safety

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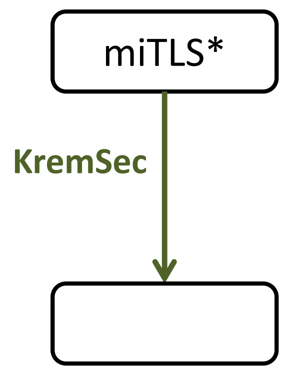

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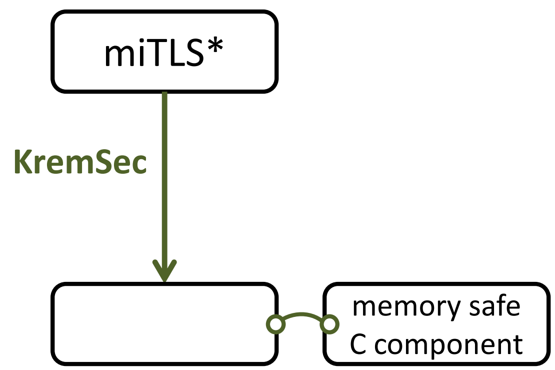

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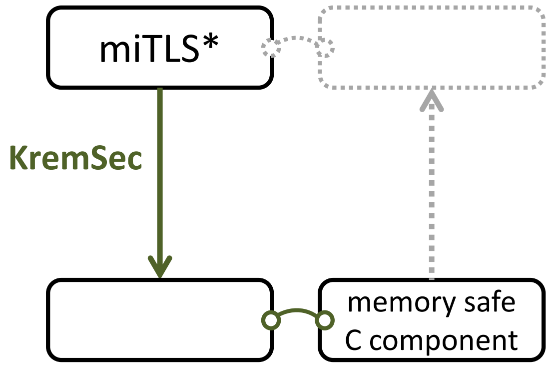

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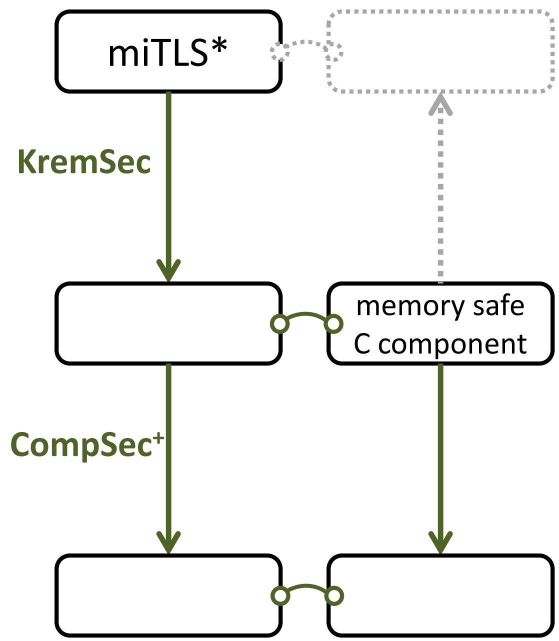

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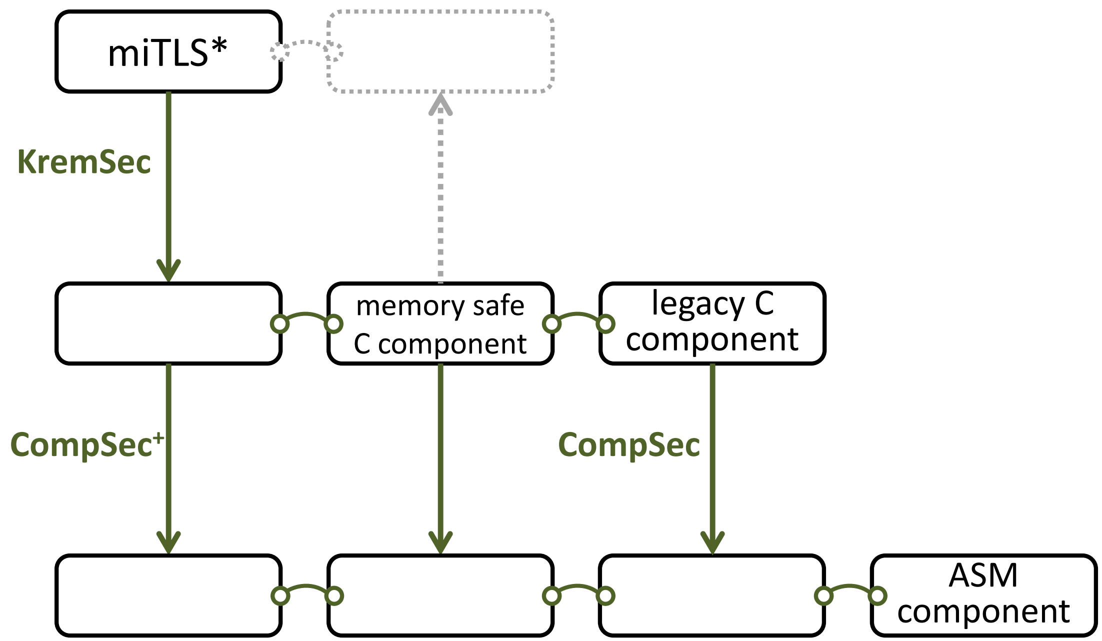

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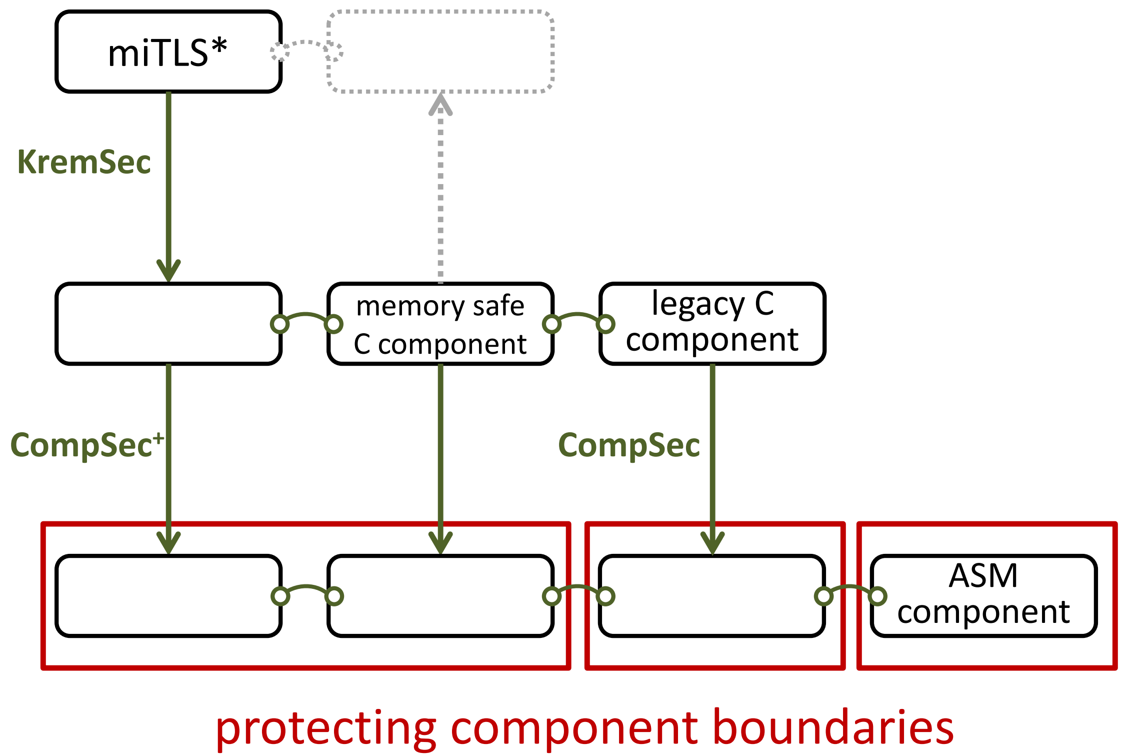

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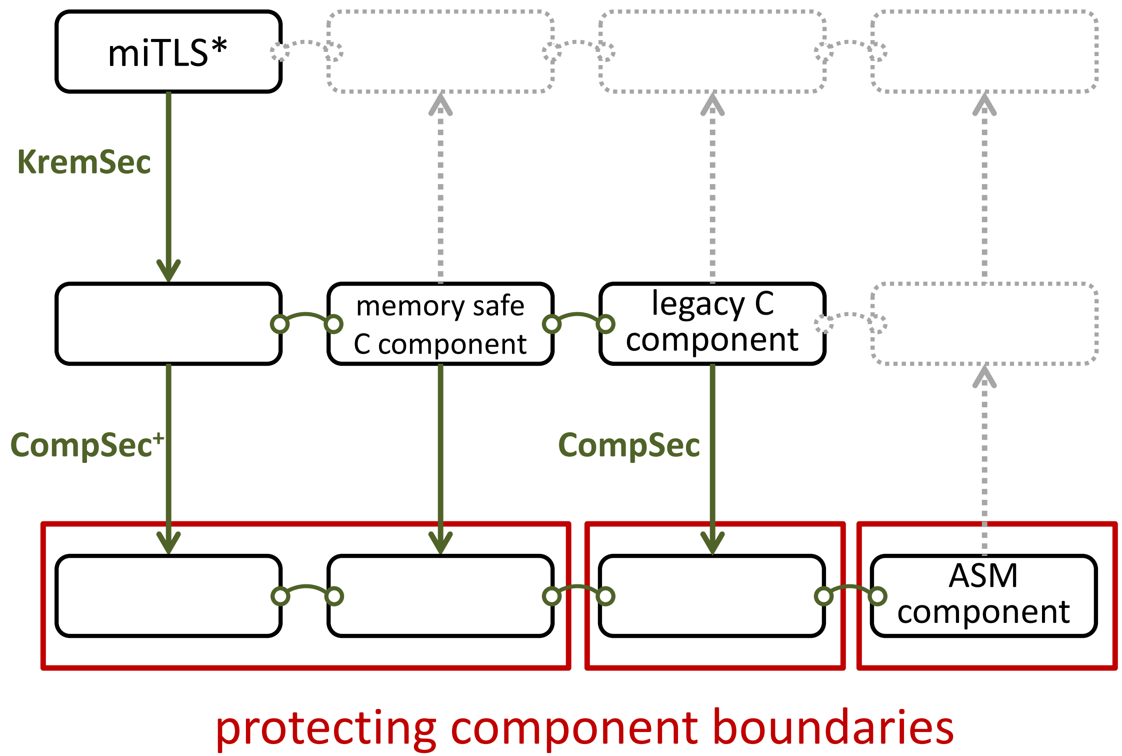

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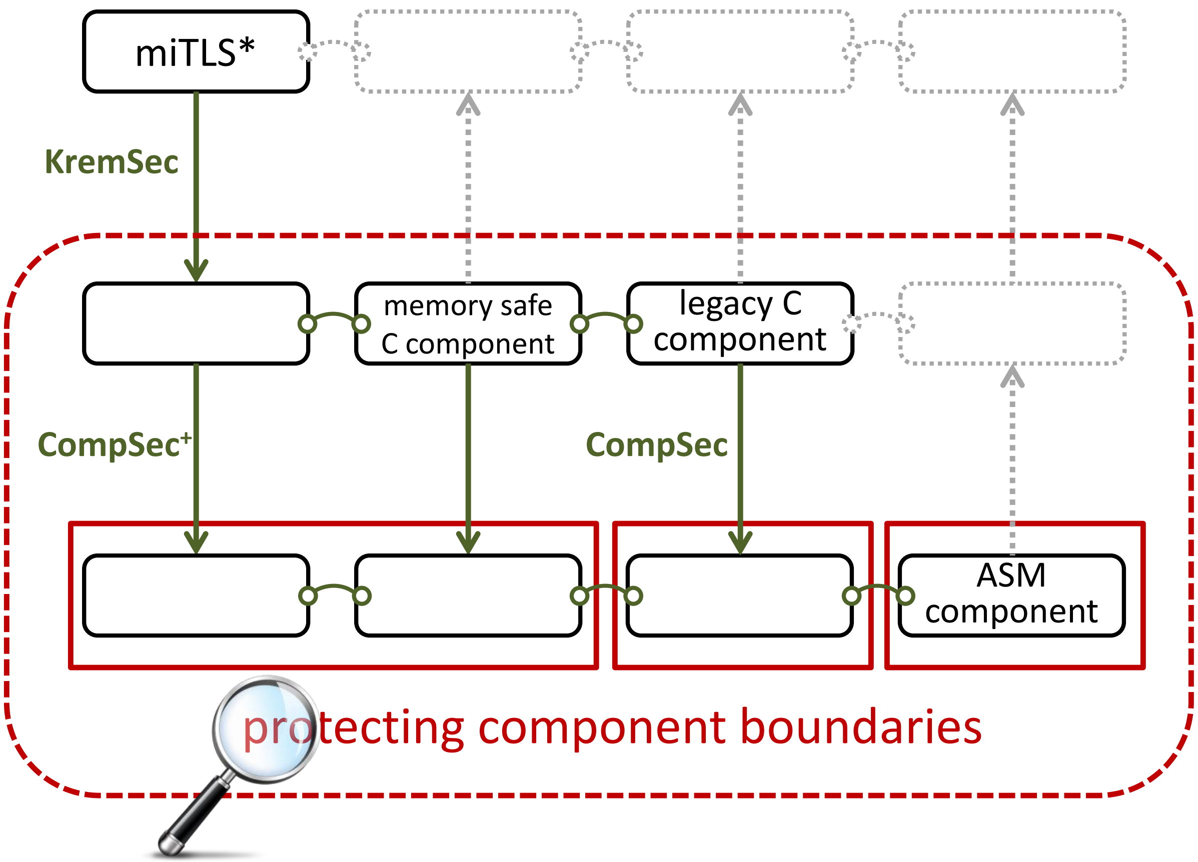


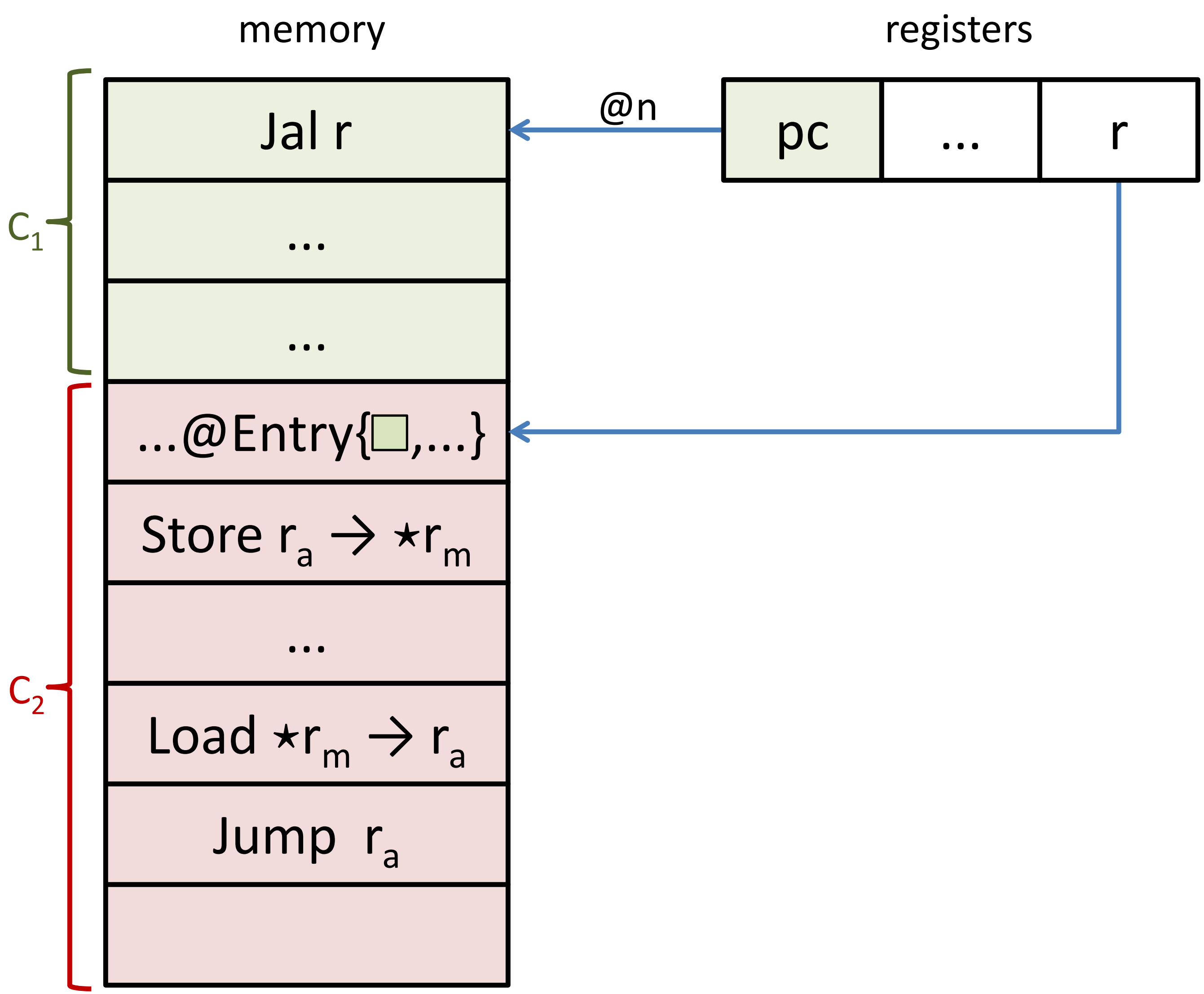
Protecting component boundaries

- **Add mutually distrustful components to C**
  - interacting only via **strictly enforced interfaces**
- **CompSec compiler chain** (based on CompCert)
  - propagate interface information to produced binary
- **Micro-policy simultaneously enforcing**
  - component separation
  - type-safe procedure call and return discipline

- **Interesting attacker model**
  - mutual distrust, unsafe source language

Ongoing work, started with Yannis Juglaret et al

Protected components micro-policy



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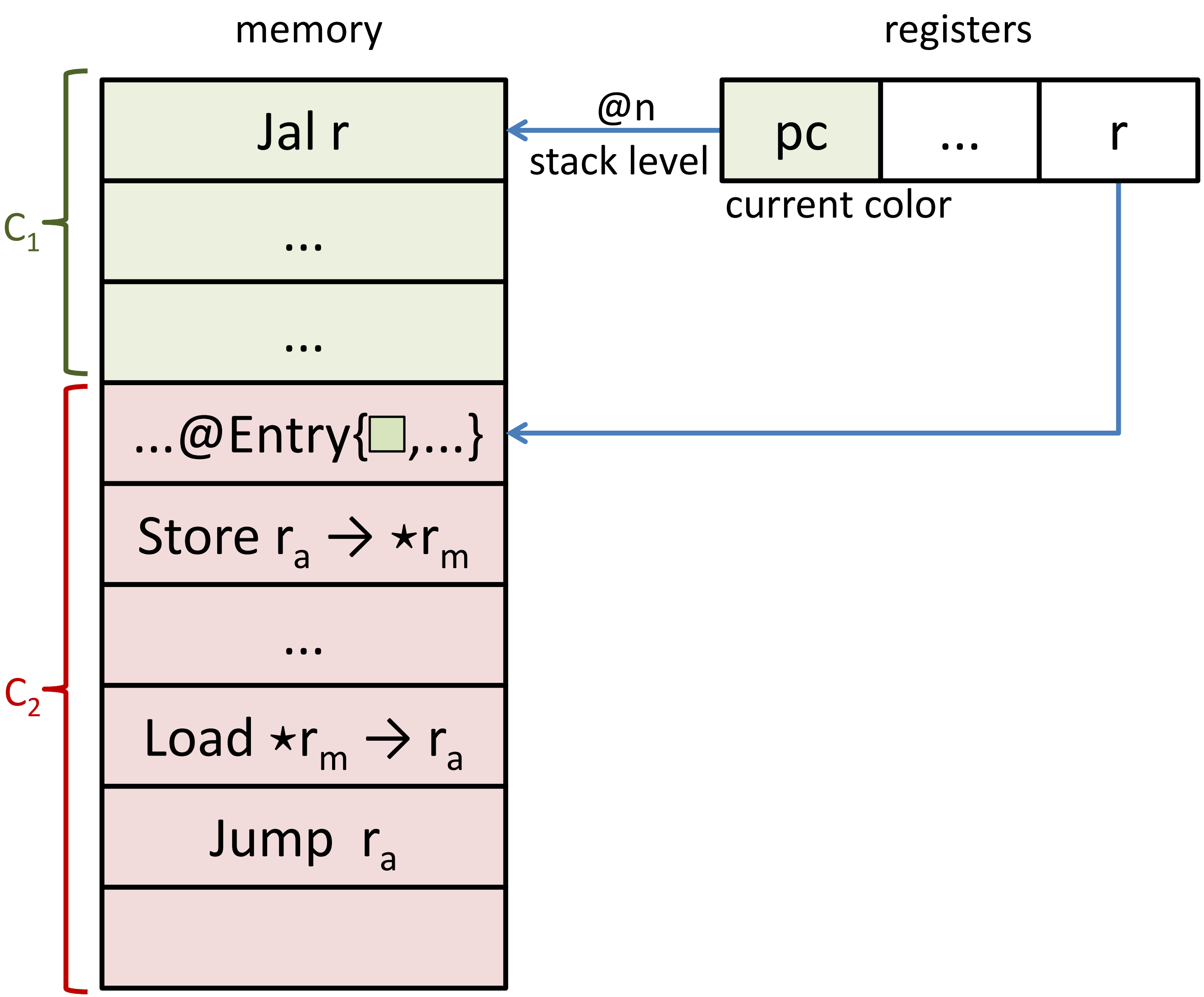

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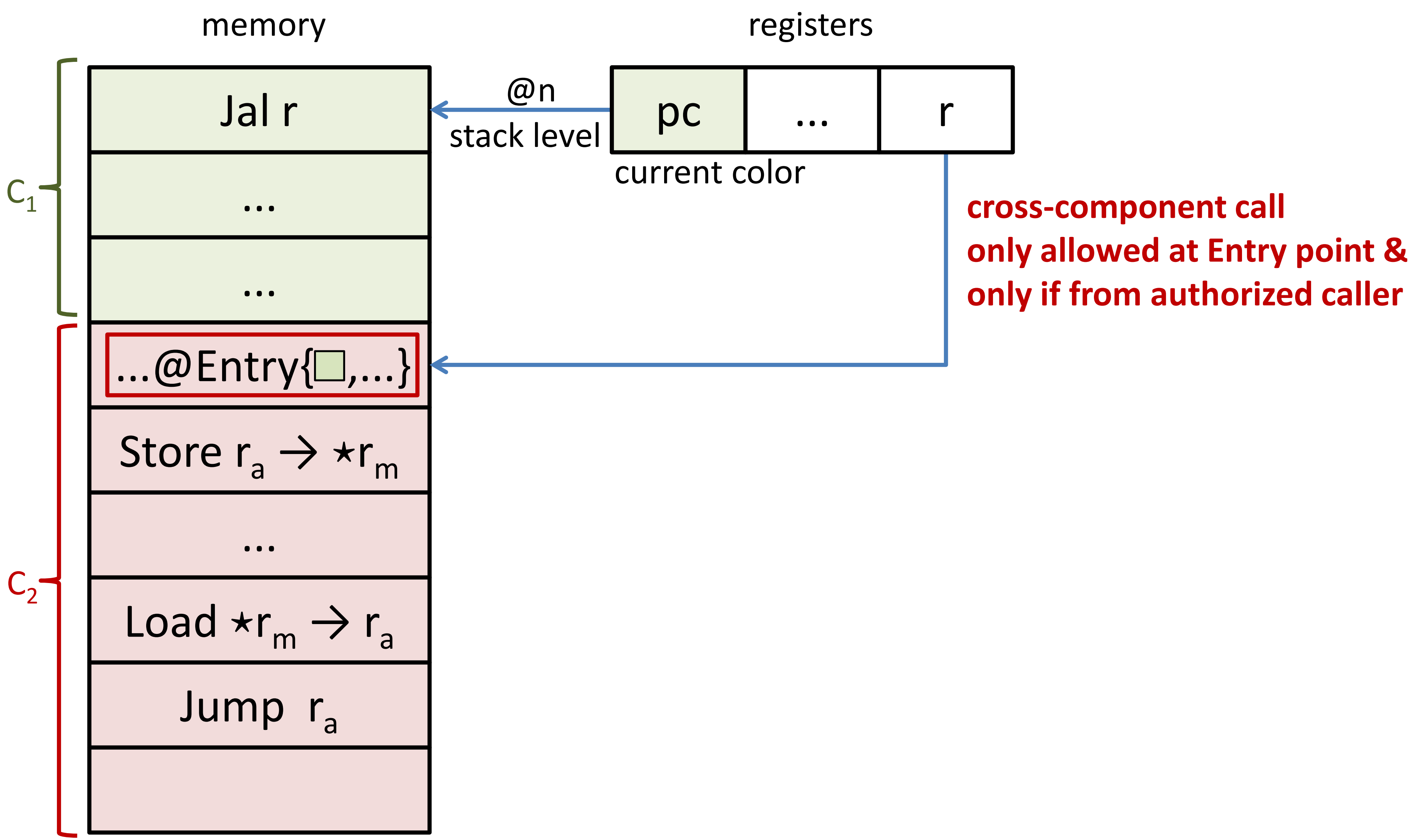

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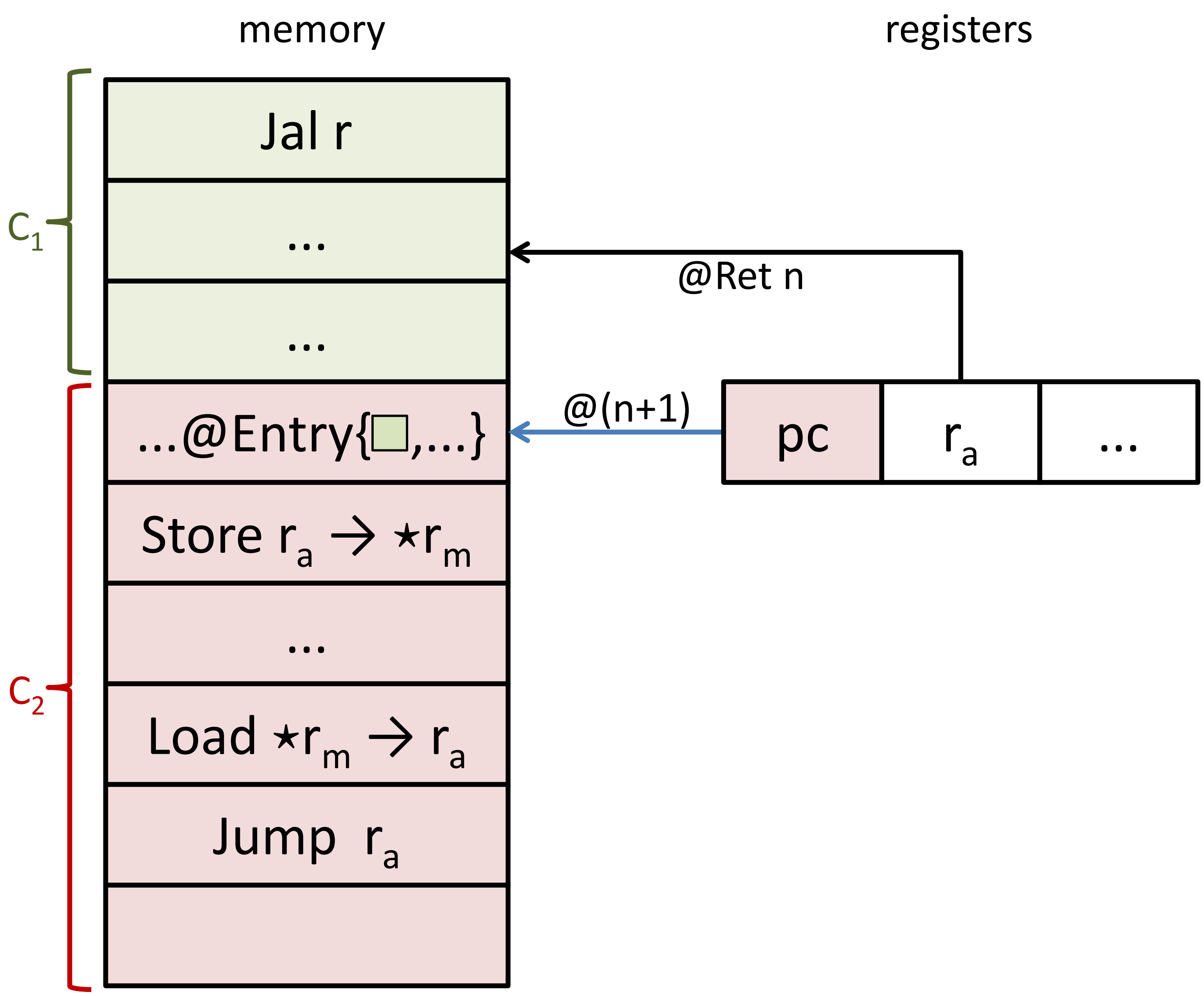

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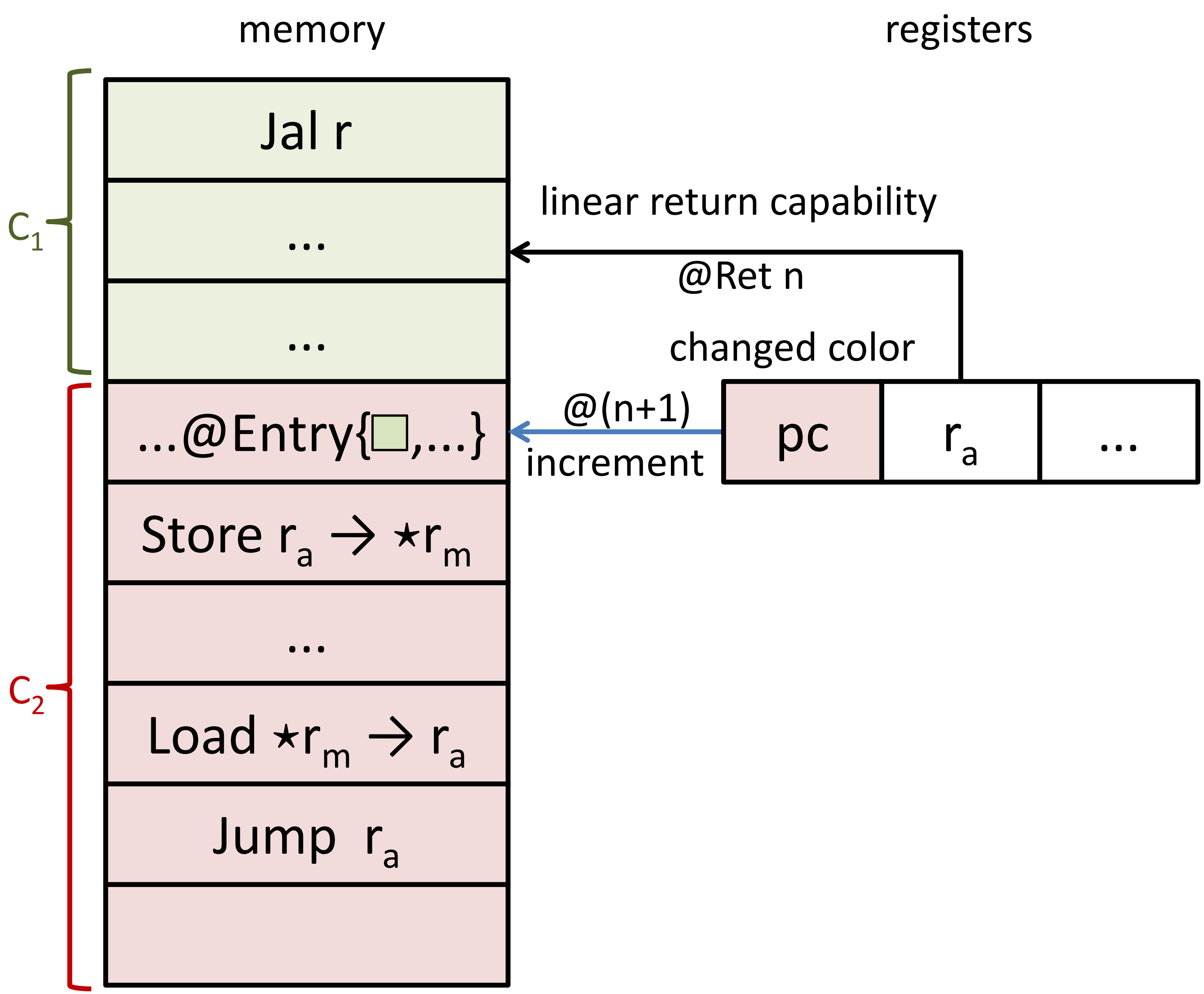

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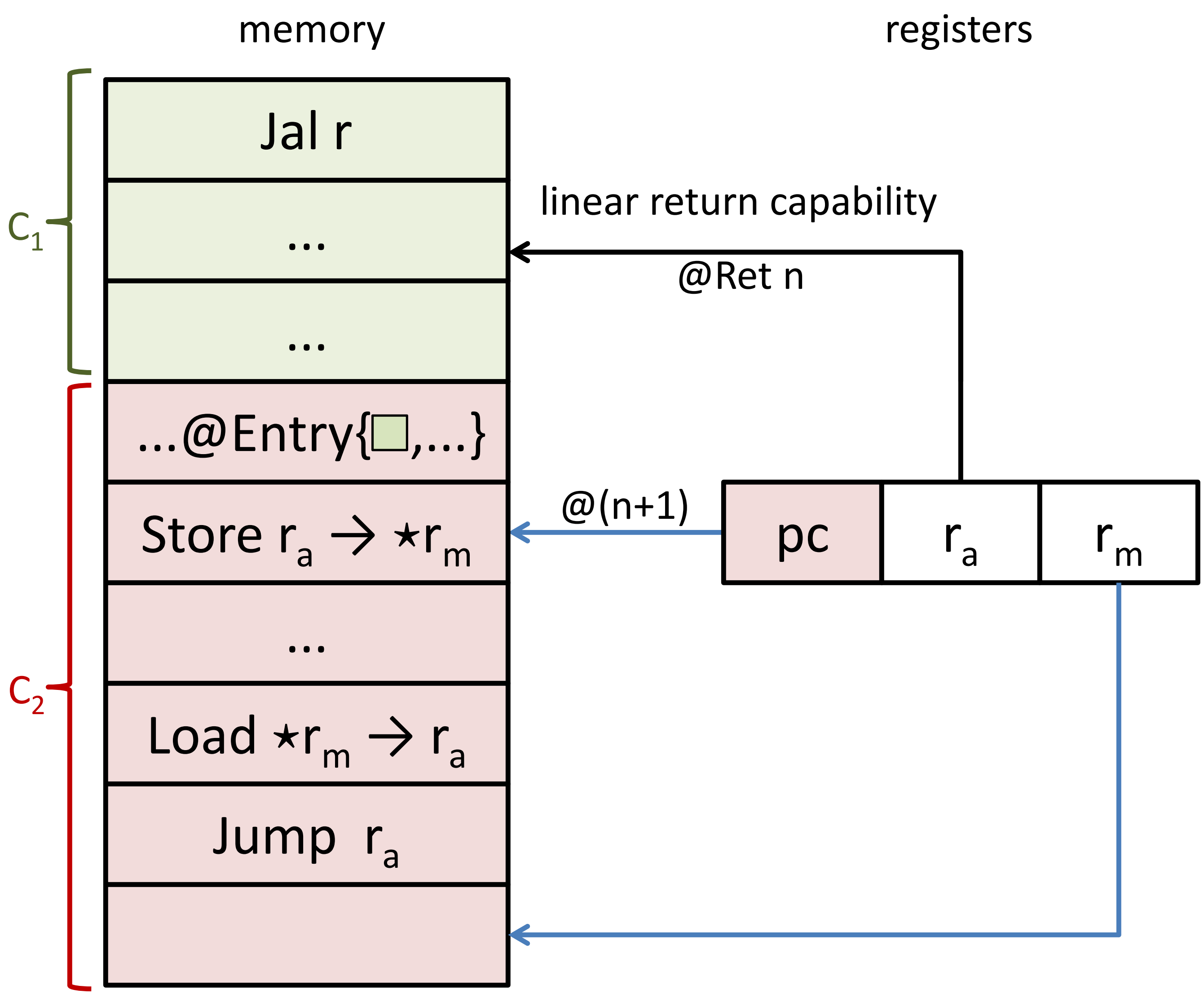

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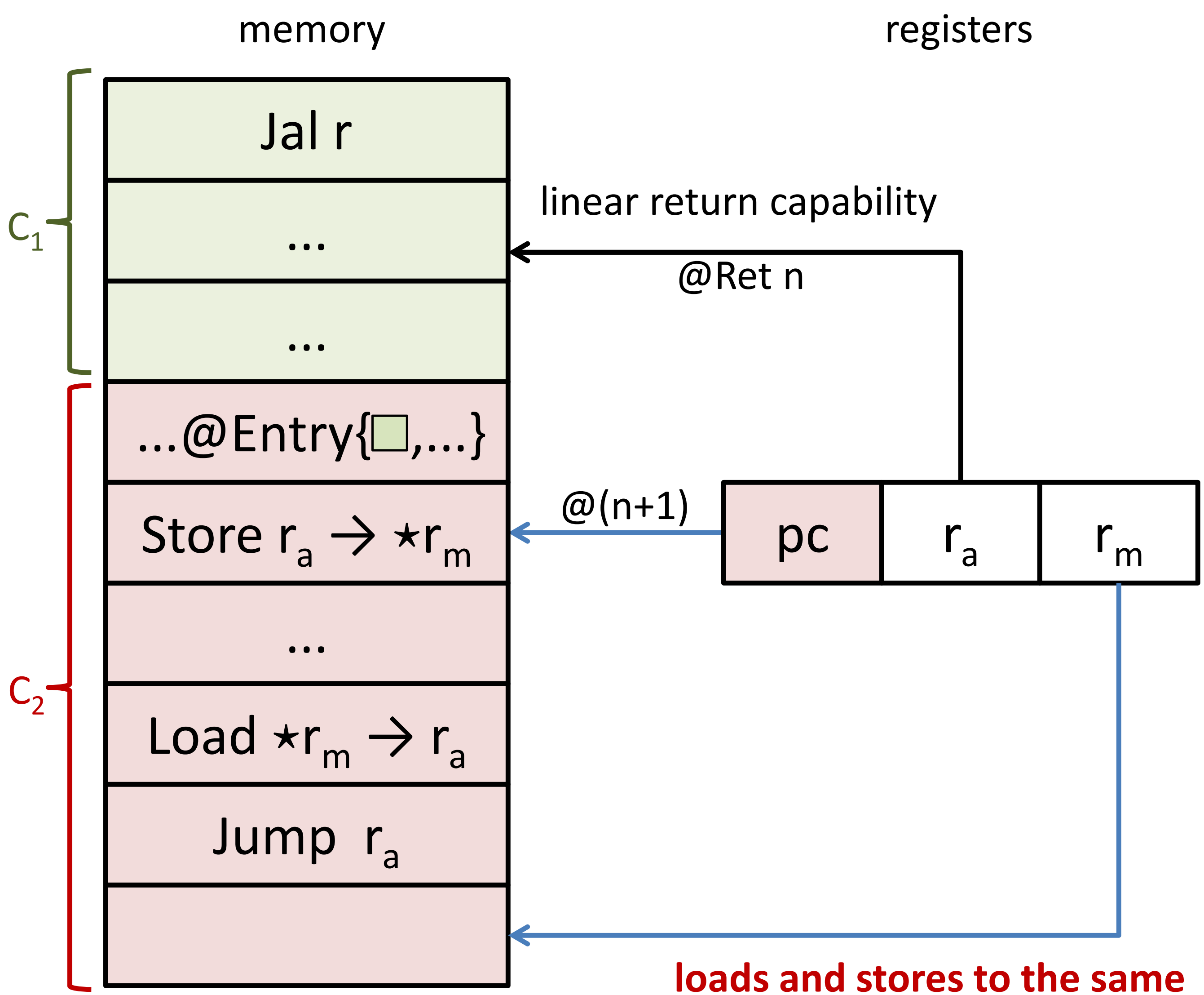
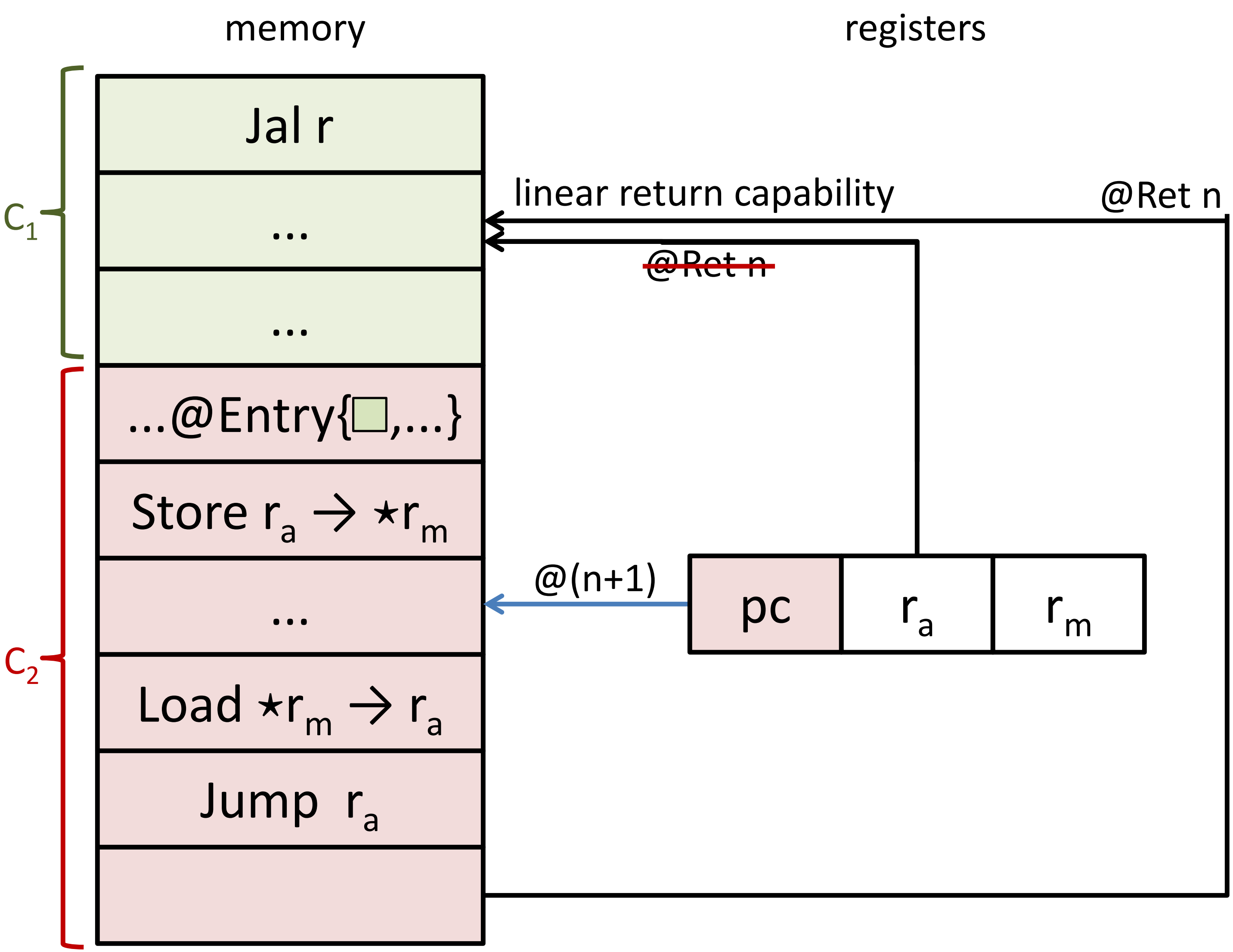


loads and stores to the same component always allowed

Protected components micro-policy



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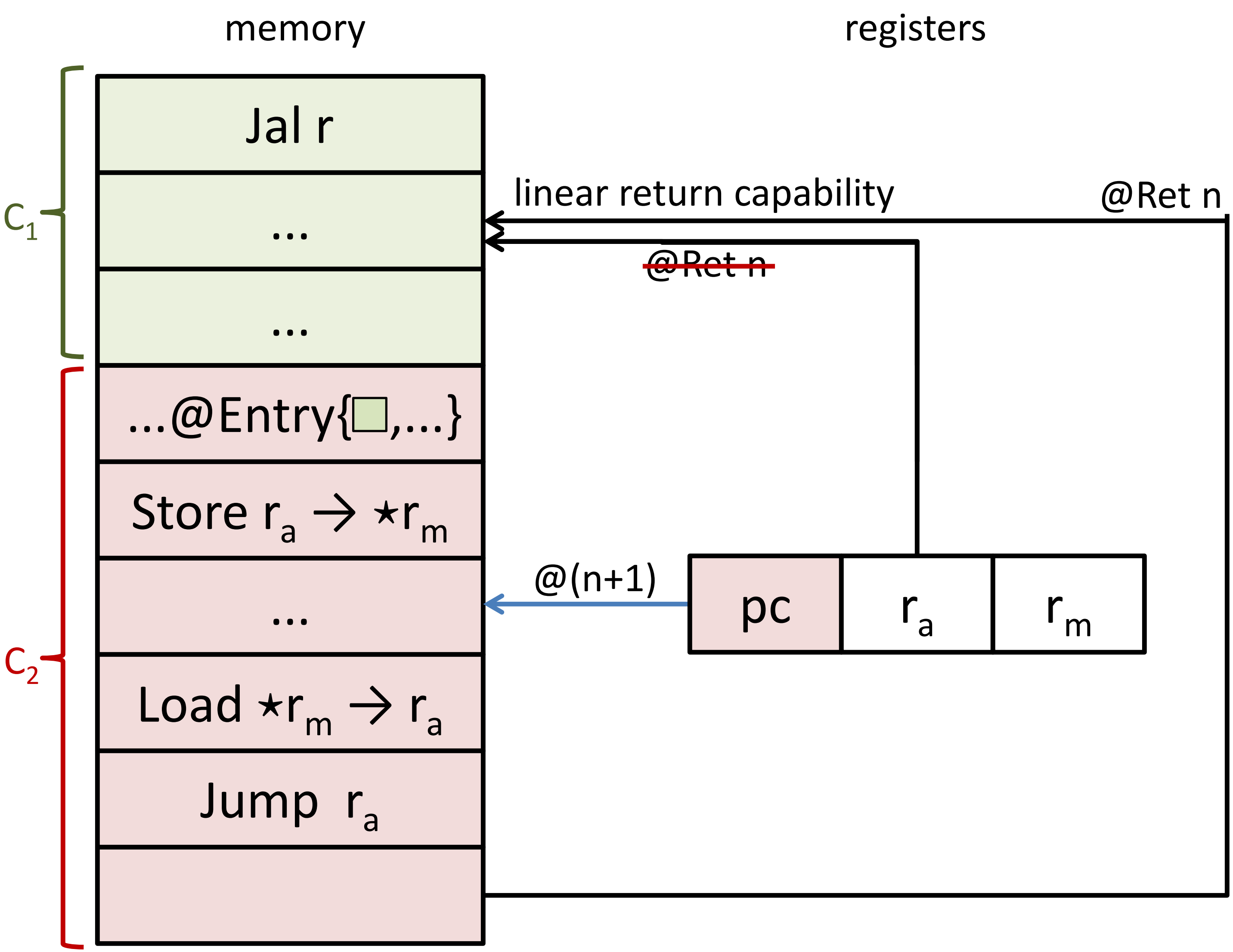

invariant:
at most one
return capability
per call stack level

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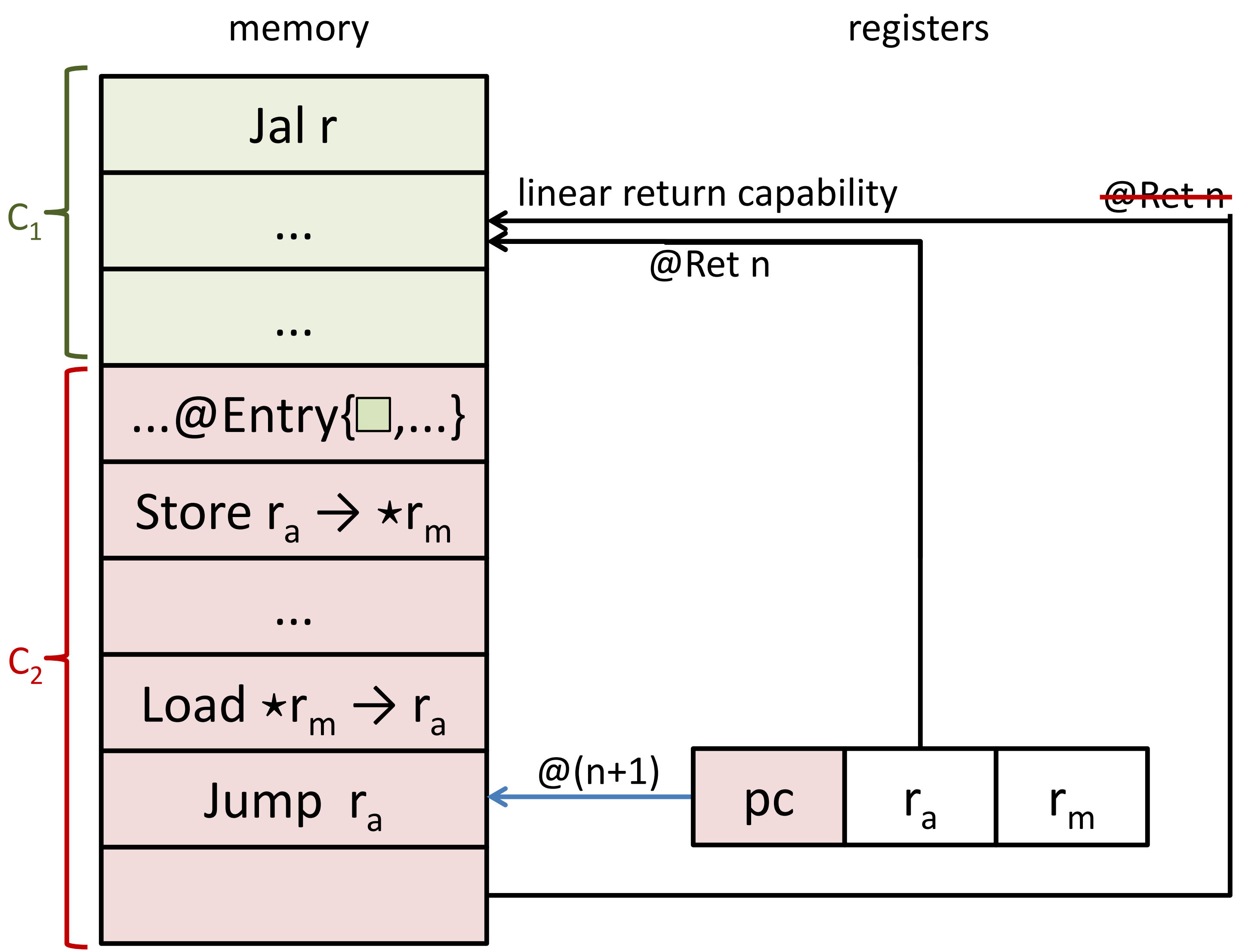

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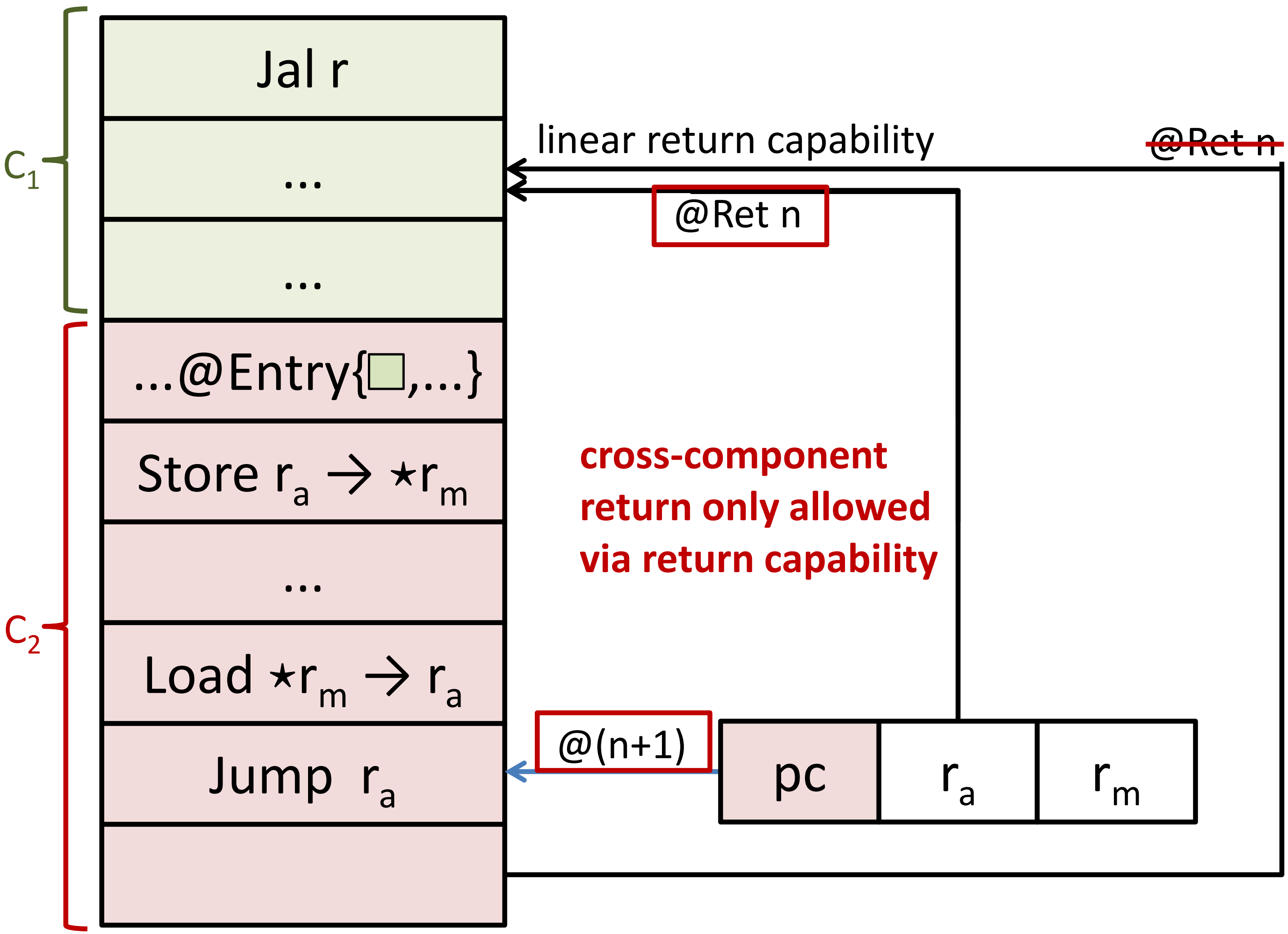

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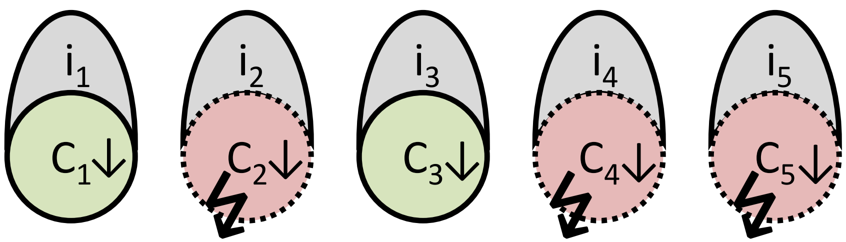
Mutual-distrust attacker model

(more interesting compared to vanilla FA or RC)

∀compromise scenarios *s*. ∀scenario-indexed trace properties *π*.

C_1 and C_3 fully defined



violates *π(s)*

∃ low-level attack from compromised $C_2\downarrow$, $C_4\downarrow$, $C_5\downarrow$

[Beyond Good and Evil, Juglaret, Hritcu, et al, CSF'16]

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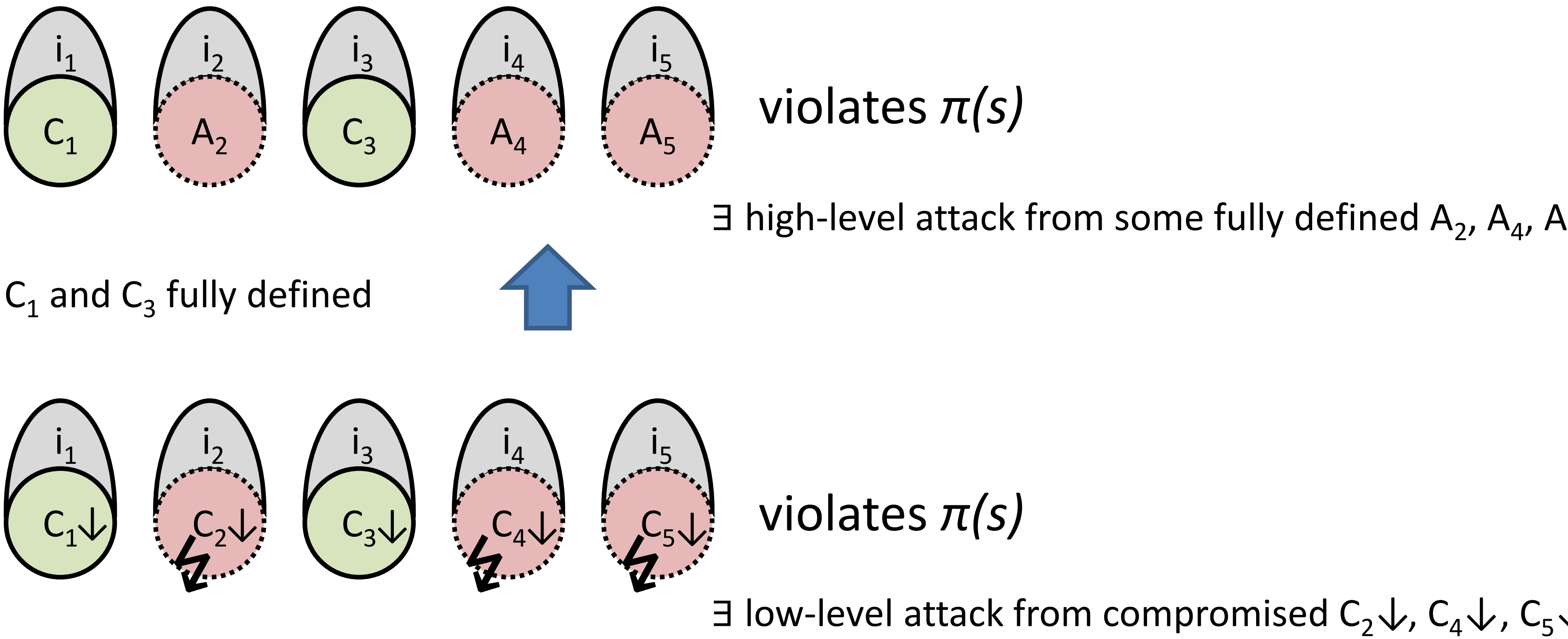

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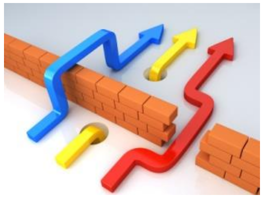
SECOMP in a nutshell

- **We need more secure languages, compilers, hardware**
- **Key enabler: micro-policies** (software-hardware protection)
- **Grand challenge: the first efficient formally secure compilers** for **realistic programming languages** (C and Low*)
- **Answering challenging fundamental questions**
  – properties/attacker models, proof techniques
  – secure composition, micro-policies for C



- **Achieving strong security properties**
  + testing and proving formally that this is the case
- **Measuring & lowering the cost of secure compilation**

- Most of this is **vaporware** at this point but ...
  – building a community, looking for collaborators, and hiring to make some of this real

BACKUP SLIDES

Protecting higher-level abstractions

- **Low*: enforcing specifications in C**
  - some can be turned into **contracts,** checked dynamically; **micro-policies can speed this up**
- **Limits of purely-dynamic enforcement**
  - functional purity, termination, relational reasoning
  - **push these limits further and combine with static analysis**

SECOMP focused on dynamic enforcement
but combining with static analysis can ...

- improve efficiency
  - removing spurious dynamic checks
  - e.g. turn off pointer checking for a statically memory safe component that never sends or receives pointers
- improve transparency
  - **allowing more safe behaviors**
  - e.g. statically detect which copy of linear return capability the code will use to return
  - in this case **unsound “static analysis” is fine**

Verification and testing

- So far most secure compilation work **on paper**
  – one can't verify an interesting compiler on paper
- SECOMP uses **proof assistants**: Coq and F*
- **Reduce effort**
  – more automation (e.g. based on SMT, like in F*)
  – integrate testing and proving (QuickChick and Luck)
- **Problem not just with scale of mechanization**
  – devising good **proof techniques** for secure compilation is a hot research topic of it's own

Remaining challenges for micro-policies

- **Micro-policies for C**
  - needed for vertical compiler composition
  - will put micro-policies in the hands of programmers
- **Secure micro-policy composition**
  - micro-policies are **interferent** reference monitors
  - one micro-policy's behavior can break another's guarantees
    - e.g. composing anything with IFC can leak

Collaborators & Community

- **Core team at Inria Paris**

  - Marco Stronati (PostDoc), Guglielmo Fachini and Théo Laurent (Interns)
  - Looking for excellent **interns**, **students**, **researchers**, and **engineers**
- **Traditional collaborators from Micro-Policies project**
  - UPenn, MIT, Portland State, Draper Labs
- **Other researchers working on secure compilation**
  - Deepak Garg (MPI-SWS), Frank Piessens (KU Leuven), Amal Ahmed (Northeastern), Cedric Fournet & Nik Swamy (MSR), …
- **Secure compilation meetings**
  - 1st at Inria Paris in Aug. 2016, 2nd at POPL in Jan. 2017, POPL workshop
  - Upcoming: Dagstuhl seminar on Secure Compilation, May 2018
  - **build larger research community, identify open problems, bring together communities** (HW, systems, security, PL, verification, ...)

Broad view on secure compilation

- **Different security goals / attacker models**
  - Fully abstract compilation and variants, **robust compilation**, noninterference preservation, ...
- **Different enforcement mechanisms**
  - **reference monitors**, secure hardware, static analysis, software rewriting, randomization, ...
- **Different proof techniques**
  - (bi)**simulation**, logical relations, multi-language semantics, embedded interpreters, ...